National Aeronautics and Space Administration

NASA SnowEx Science Plan:

Assessing Approaches for Measuring Water in Earth's Seasonal Snow

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v.1.6.

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Cover: Satellite imagery, airborne sensor data, and field photographs from SnowEx 2017:

a) Worldview Stereo image of west Grand Mesa (Colorado) at the onset of the SnowEx 2017 airborne and field campaign (1 February 2017).

b) Sunset over snowy west Grand Mesa. Photo taken near TLS Site-F on 9 February 2017 (courtesy: Chris Hiemstra).

c) Snow depth map from the NASA Airborne Snow Observatory over the Senator Beck Basin study area (courtesy: Delwyn Moller and the ASO team).

d) Ka-band mapping of snow from GLISTIN-A over Grand Mesa (courtesy: Delwyn Moller and the ASO Team)

e) SnowEx survey marker, one of many deployed across the study areas

f) Scientists measuring vertical snow properties in a “mega snowpit”

Executive Summary

Despite snow's unique importance to the global Earth system, no single satellite-borne sensor has been demonstrated to accurately measure all of the planet's snow water equivalent. Seasonal snow cover is the largest single component of the cryosphere in areal extent, covering an average of 46 million km^2 of Earth's surface (31% of land area) each year, and is thus an important expression of and forcing of the Earth's climate. In recent years, Northern Hemisphere snow cover has been declining at a rate greater than Arctic sea ice. More than one-sixth of the world's population (~1.2 billion people) relies on seasonal snowpack and glaciers for their water supply. Snowmelt-generated water supply is likely to decrease this century. Snow is also a critical component of Earth's cold regions ecosystems where wildlife, vegetation and snow have strongly interconnected fates.

To understand the time and space variation in the snow's energy and mass balances along with the extensive feedbacks with the Earth's climate, water cycle, and carbon cycle, it is critical to accurately measure snowpack. The ability to measure snow cover fraction and albedo from space is a proven technology and has yielded tremendous advances into our understanding of the Earth system. Indeed, the most recent Earth Science Decadal Survey (ESDS) recommended the *Surface Biology and Geology (SBG)* as an imperative "Designated measurement". SBG would include a visible through shortwave infrared imaging spectrometer and spectral thermal imager for understanding snow spectral albedo, the controls on snow albedo, and snow surface temperature. However, the great diversity in snowpack characteristics (e.g., depth, liquid water content) and cold regions environments (e.g., forests, complex terrain, barren tundra) pose a great challenge for measuring global snow water equivalent (SWE). The international snow remote sensing community has been active in responding to this challenge, and has developed a number of snow remote sensing technologies. For example, the NASA Cold Lands Processes Experiments significantly advanced microwave radar technology to estimate SWE. While airborne SWE and albedo measurement has been successfully applied at the watershed and regional scale, several spaceborne SWE missions have been proposed but ultimately were not been selected; additional missions to map SWE are currently in development globally. There are several new approaches that have been proposed, e.g., using L-band measurements from UAVSAR to measure SWE. The ESDS has recommended a *Snow Depth/SWE* concept based on radar, InSAR, or LiDAR as a to-be-competed Explorer measurement. Only by intercomparing the various measurement techniques will we be able to quantify their capabilities in different environments, as well as possible multi-sensor synergies in the context of modeling and data assimilation for future global SWE mapping in an integrated Earth System framework.

To better characterize the performance of proposed sensors, and to identify optimum multi-sensor synergies and model assimilation for mapping the critical snowpack properties in future satellite missions, the SnowEx campaign was undertaken by the NASA Terrestrial Hydrology Program (THP). The project aims to quantify and compare capabilities and limitations of traditional and newer snow estimation techniques across a range of environmental conditions, with an emphasis on articulating satellite remote sensing strategies and requirements. The newer technologies hold great promise but need to be tested more extensively with airborne observations alongside existing technologies for a comparison of their relative accuracy and global applicability. Advances in snow modeling and data assimilation must be further leveraged to integrate measurements from multiple sensors to estimate SWE. Remote sensing of components related to the snow surface energy balance - including albedo and surface temperature - are critical for understanding energy cycles and changes in climate and are also a significant opportunity for understanding changes in SWE as well as improved SWE estimation through assimilation.

What is SnowEx? SnowEx is a five year program initiated and funded by NASA THP to address the most important gaps in snow remote sensing knowledge. It focuses on airborne campaigns and field work, and on comparing the various sensing technologies, from the mature to the more experimental, in globally-representative types of snow. The goal is to address the most important gaps in our snow remote sensing knowledge, and thus lay the groundwork for a future snow satellite mission. SnowEx was initiated in the 2016-2017 winter with a field campaign that was designed to evaluate the sensitivity of different snow remote sensing techniques to increasing forest density. In the remaining years, SnowEx campaigns will focus on the efficacy of SWE measurement and modeling techniques in up to four regions of interest:

1. Mountain ranges and temperate forests of the western United States
2. Boreal forests (taiga) and arctic tundra of North America
3. Cold prairies in interior regions of North America, and/or
4. A maritime gradient spanning the Pacific Northwest region of the United States

The process for recommending these focal areas is documented further in this science plan.

Science Plan and Implementation - The high variability of global snowpack conditions requires a systematic investigation of sensor capabilities and sensitivities across a range of environments and spatial and temporal scales. Identification of a robust system for mapping SWE (and related snow characteristics) with multiple remote sensing instruments and data assimilation will provide direct guidance for designing a future snow satellite mission. Such a system would in turn provide unprecedented knowledge of snowpack quantity and how it varies over seasonal and annual scales across the globe, thereby transforming watershed and ecological management and climate monitoring. A future snow satellite mission, informed by SnowEx experiments, would enable estimation of the critical snow properties on a global scale, with the greatest scientific return coming from depth/SWE measurements and coincident spectral albedo and snow surface temperature.

The geographical focus of SnowEx is proposed as North America (Fig. ES1), which contains the six broad snow climate categories identified in the literature: tundra (alpine or Arctic), taiga (Boreal forest), warm (temperate) forest, maritime, prairie, and ephemeral. Additional factors that transcend these snow climates include terrain complexity (e.g., steep vs. flat terrain), and snow states like wetness. The timing and location of specific campaigns is envisioned as a combination of opportunistic as well as targeted choices, and planned to leverage complementary or similar airborne and field efforts external to SnowEx. Specifically, SnowEx leveraged Airborne Snow Observatory (ASO) operations (2013-ongoing) in the 2016-2017 northern hemisphere winter in Colorado and will do so again in the 2018-2019 winter over a broader domain that also includes California and Idaho. In the 2019-2020 winter, SnowEx will focus on snow in boreal forests and Arctic tundra in conjunction with the NASA ABoVE campaign (2014-2024). The final field campaign is proposed to address remaining gaps: we describe two candidate sites, one in the cold prairies of the northern contiguous United States and southern Canada, which presents an opportunity to test snow remote sensing techniques in an environment that is extensive globally, and one in the maritime zone of the Pacific Northwest, which presents an opportunity to test snow remote sensing techniques in a unique environment with multiple sensing challenges (deep snow, wet snow, persistent cloud cover, and dense forests). Discussions on the focus of SnowEx 2021 are still ongoing.

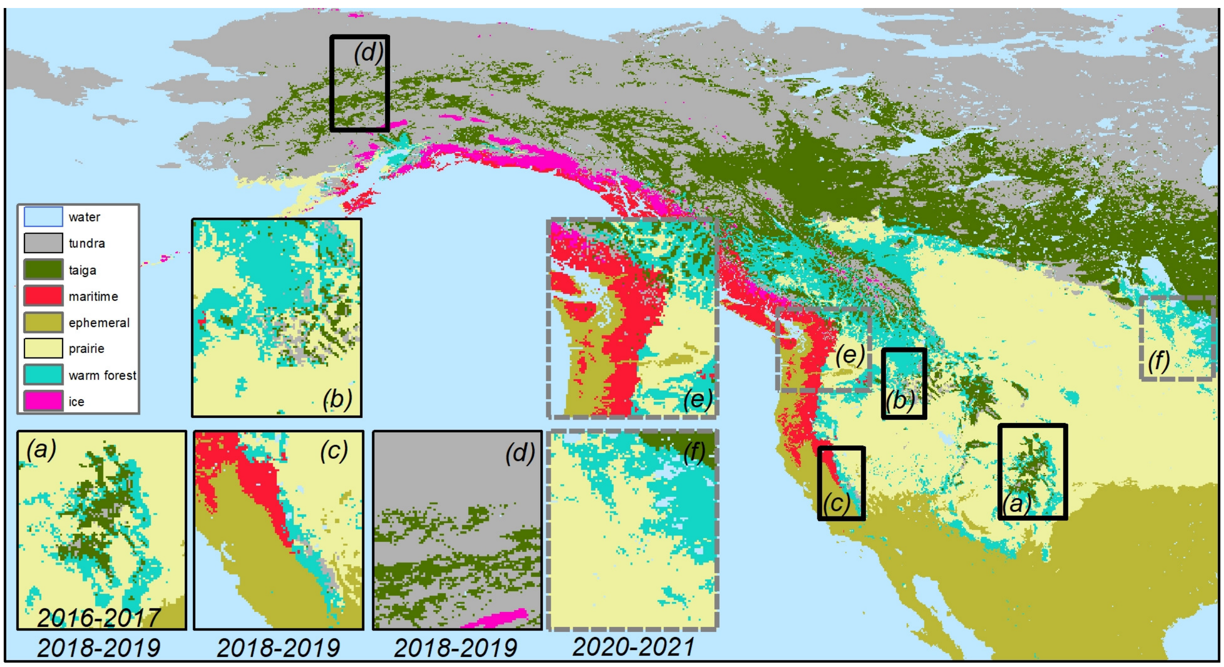

Figure ES1. Map of SnowEx study domain in western North America and snow climates (Liston, 2004). Shown in the inset maps are the proposed focus regions for the field campaigns. The 2020-2021 campaign includes notional site locations for alternative campaigns across a maritime gradient (e) and a cold prairie (f)

The suite of SnowEx field campaigns will include coordinated airborne and field surveys to characterize snowpack at multiple periods during the cold season. Intensive airborne and field data collection will also occur during the snow-free season to obtain baseline surveys (e.g., snow-free elevation mapping for altimetric approaches). Ground-based remote sensing and *in situ* observations will be collected by members of the snow science community, and these will serve as reference datasets for assessing the quality and accuracy of airborne data and models. Application of process-based snow models and data assimilation experiments will provide further insights into optimal strategies and concepts for monitoring global snowpack in a future mission.

SnowEx Outcomes and International Engagement - SnowEx will provide key insights into optimal strategies for mapping global SWE with remote sensing and models, which will enable a competitive proposal for a Decadal Survey “Earth System Explorer” mission. The systematic assessment of methods for mapping water and energy components of seasonal snow in SnowEx is fully aligned with the objectives of the NASA Terrestrial Hydrology Program and the Earth Science Division as well as the ESDS. As any future snow satellite mission will require observations from an international collection of satellites, engagement with the international snow science community is central to the success of SnowEx. Realization of a global snow mapping program requires coordination with international partners and space agencies (e.g., Canada, Europe, China). SnowEx is directly responsive to recommendations from the international community (e.g., World Meteorological Organization) to test snow measurement techniques across vegetation gradients and climates, and to develop systems that incorporate models and remote sensing data to characterize snowpack states.

1. Motivation

Seasonal snow cover is the largest single component of the cryosphere in areal extent, covering an average of 46 million km^2 of Earth's surface (31% of land area) each year. The high albedo and low thermal conductivity of snow affects global climate, and in turn snow responds to changes in global and regional climate. The magnitude of snow accumulation and timing of snowmelt drives seasonal water cycles in many regions. More than one-sixth of the world's population (~1.2 billion people) relies primarily on water from seasonal snowpack and glaciers. In California, e.g., more than 70 percent of water from the San Joaquin River, which originates from Sierra Nevada snowpack, is used to irrigate the Central Valley. Although only two percent of U.S. cropland is in the Central Valley, it produces about 300 varieties of crops and nearly half the nation's fruits and nuts. The economic value of natural snow reservoirs for agriculture and water resources is estimated in the trillion dollar range in the western United States alone; the climate benefits of seasonal snow are likely even greater [Sturm et al., 2017]. The myriad important roles of snow in the Earth system was prominently recognized under multiple elements in the latest Earth Science Decadal Survey [*National Academies*, 2018]. These include precipitation, glaciers and ice sheets, water stored on land, surface characteristics, terrestrial vegetation/ecosystems, ice surfaces, sea level rise, and snow amounts/melt rates].

The international snow community currently lacks a comprehensive satellite-based approach for routine mapping of the global distribution of snow water equivalent (SWE), the essential snow hydrologic variable for all water-related studies and applications. SWE, the measure of total water stored in snowpacks, is changing rapidly on an annual basis as seasonal snowpacks are often accumulating later, reaching lower maximum values, and melting earlier as the climate warms. Remotely sensed snow covered extent and snow albedo provide important but indirect information about the evolution of SWE and snowmelt through time. The 2017 Decadal Survey [*National Academies*, 2018] has recognized the need for accurate quantification of snow spectral albedo and the physical properties controlling that albedo with measurement in the "Designated" category, as well as improved mapping of SWE and melt rates and included these in the "Explorer" category, for which three competed launch opportunities are anticipated in the mid-2020s. Current and planned missions do not have adequate space-time sampling (e.g. GEDI and IceSat-2), are not well-configured for snow measurements (SWOT), are not high enough spatial resolution (passive microwave) or need to be further tested and validated (e.g. estimating SWE from L-band on NISAR). Considering the years of lead time required for a successful mission proposal, the preparation must be done now. While substantial advances have been made in the last five years at estimating SWE with airborne missions at the synoptic scale across mountain systems, capabilities of individual remote sensing instruments have not yet proven adequate to capture these changes from space on a global scale. Because of the spatial and temporal variation in snow and landscape characteristics - each of which poses unique measurement challenges - it is likely that multiple sensors and model integration are needed to map SWE globally. Therefore, there is a need for focused airborne and field campaigns executed across a range of snow environments to evaluate current remote sensing capabilities and opportunities for estimating SWE globally in a future satellite mission.

The proposed SnowEx ("snow experiment") is the critical step needed to develop a competitive mission proposal. SnowEx is a community-wide effort aimed at identifying the optimum combination of remote sensing technologies that can provide accurate spatial estimates of global snow mass in various contexts, and at sufficiently high precision. To achieve this goal, SnowEx will perform a series of field and airborne experiments across multiple kinds of snow and confounding factors, and integrate these within the context of models, to validate remote sensing technologies. While the primary variable of interest is SWE, it is recognized that measuring components of the snow energy balance, which enable understanding of changes in the thermal state of the snowpack, is critical to understanding SWE dynamics. Indeed several years of work on "SWE reconstruction" uses remotely sensed snow cover depletion and modeled energy balance to infer SWE retrospectively [*Molotch et al., 2015*], while recent work illustrates that assimilation of reflectances can improve snow depth estimates [*Charrois et al.*, 2016]. In order to obtain a complete picture of snowpack dynamics and to build methodologies for leveraging more mature technologies, SnowEx also includes measurements of snow albedo (shortwave) and snow surface temperature (infrared). The data produced by SnowEx will develop and demonstrate sensor and model fusion techniques suitable for future deployment on satellites designed for measuring global SWE.

Assessing techniques that are optimal for mapping global SWE requires community engagement as well as national and international partnerships. The snow community recognizes that global snow sensing is a complex challenge that requires a wide range of expertise (remote sensing, field validation, modeling and assimilation) in order to maximize the potential for success. Earth science missions proposed in the past provide ample evidence that a strong community effort is a necessary ingredient for success [e.g., Aquarius, Lagerloef et al., 2008; SMAP, Entekhabi et al., 2010], and a community effort maximizes community support. We have seen that the mission selection process is rigorous [National Research Council, 2007; CoReH2O, Rott et al. 2010], and consequently, our vetting of a snow mission concept must be equally rigorous. Broad community engagement in SnowEx is therefore a necessity that will ensure a balanced and thorough approach. Furthermore, SnowEx will seek partnerships with related efforts to identify synergies and enhance scientific opportunities, for example, the NASA Terrestrial Ecology Program Arctic-Boreal Vulnerability Experiment (ABoVE). SnowEx will also coordinate with international partners and snow-related missions. For example, CSA is proceeding with an EE10 concept [Lemmetyinen et al., 2018] that has been submitted to ESA, and China plans to launch WCOM [Xiong et al., 2016]. It is recognized that an international approach may be the only practical way to obtain the multi-sensor observations needed to map SWE in all Earth's snow covered regions. Indeed, a global SWE mission requires global partnerships.

The snow community is currently at a critical stage. The science questions have been articulated, candidate technologies are available, and ongoing community activities (e.g., International Snow Working Group Remote Sensing, iSWGR) have shown a need to demonstrate that recent developments can lead to global capabilities. At the 2014 iSWGR workshop [Sturm et al., 2014], the snow community recognized that finding optimum combinations of sensors and models in order to enable mission trade studies would require multi-sensor field and airborne observations for which data did not exist—particularly incorporating new developments from the past several years in remote sensing, our understanding of snow/radiative transfer physics, and modeling/assimilation. In fact, the last preceding major multi-sensor snow campaign, CLPX-1 in 2002-3, was fifteen years ago. Field experiments in the U.S., Canada, and Europe over the past fifteen years have provided crucial groundwork, and preliminary evaluation of some of the technologies. Over this period, the community has grown and learned a tremendous amount, and there have been many new technological developments and modeling advances. SnowEx will build on these recent experiments and will produce a proposed sensor and model fusion approach, with both theoretical and experimental scientific rationale, for a future snow mission.

2. Relevance

SnowEx will support the snow component of at least two missions in the National Academies' 2017 Decadal Survey: (1) the "Earth System Explorer" specifically targeted at measuring global snow depth and snow water equivalent, and (2) the the hyperspectral imager selected as a "Designated Mission" targeted at "Surface Biology and Geology." The overarching question of SnowEx is aligned with multiple Earth Science/Application objectives in the 2017 Decadal Survey, including H-1b "Quantifying rates of precipitation and its phase..." and H-1c "Quantifying rates of snow accumulation, snowmelt, ice melt, and sublimation from snow and ice worldwide at scales driven by topographic variability." Both of these objectives were rated as "most important" for science and applications. SnowEx directly addresses these objectives through identification of the optimal suite of remote sensing modeling approaches for quantifying SWE and the snowmelt energy balance across landscapes with variable topography and forest cover.

The objectives of SnowEx support the NASA Terrestrial Hydrology Program's objective "to develop new observational basis for water resources management". The recent success of the NASA Airborne Snow Observatory has demonstrated the demand for more detailed snow information from the integration of remote sensing and modeling and the potential for applications in water resources management. SnowEx will provide quantitative guidance for the optimal combination of snow remote sensing instruments and models, which in turn has potential to provide a new observational basis for water management across a broad geographic domain. This helps address the top recommendation of the Decadal Survey's Water Panel: "an integrated earth system framework using satellite observations and models", spanning all parts of the water cycle.

As a space agency and as a research agency, NASA's motivation for any Earth Science satellite mission must consider both science questions to be answered for the sake of science as well as providing data to demonstrate specific societal applications (operational applications are the job of operational agencies). NASA has yet to launch a mission focused on seasonal snow, arguably because (1) demonstration of snow sensing techniques has been limited; and (2) as a community, we have lacked a focused community effort to determine the optimal sensor strategy for spaceborne monitoring of snow, across a range of climates and snow conditions. With seasonal snow as a major Explorer observable within the Decadal Survey, we require field and airborne experiments to demonstrate sensor and model fusion approaches, to prepare us to design a seasonal snow spaceborne mission within the next 5 years.

The SnowEx approach to focus on gradients of confounding factors such as forest cover, and topography addresses recommendations made by the World Meteorological Organization (WMO) Integrated Global Observing Strategy (IGOS) report on the cryosphere [IGOS, 2007]. The focus of SnowEx on SWE across a gradient of forested regions meets the recommendation "*Priority should be given to research and development of algorithms and new sensors to measure SWE, under a wide range of vegetation conditions.*" The strategy for targeting multiple environments and variables related to SWE evolution are also captured in SnowEx and address the IGOS recommendation "*Targeted field projects should be conducted to deal directly with the measurement of snow in multiple environments. These should seek to advance coordinated remote sensing of snow albedo and surface temperature (i.e. optical measurements) together with SWE and snow depth (i.e. microwave measurements)*." Finally, SnowEx aims to leverage remote sensing data with snow models through data assimilation supports the IGOS charge "*Integrated multi-sensor data fusion and global analysis systems that blend snow observations from all sources must be improved. The ideal global snow observing system will use observations from all relevant sources in coherent, consistent high-resolution analyses of (at a minimum): the extent of snow cover, snow depth, SWE, snow wetness, and albedo*."

3. Prioritizing SnowEx Activities

The goal of this section is to review the current state of the science of remote sensing of snow as a basis for defining priorities for SnowEx. We focus this review using the SnowEx overarching science questions identified through a rigorous process based on focused exercises at multiple community workshops, and consensus rankings by the SnowEx Steering team. This led to the overarching question: "***What is the distribution of snow-water equivalent (SWE), and the snow energy balance, in different canopy types and densities, and terrain?***".

The prevailing technological understanding is that different remote sensing techniques will work better for different snow types. For instance, deep mountain snow (complex terrain), which is important for water resources, though limited in areal extent globally, requires high resolution measurements, but can be largely characterized via its depth (e.g. lidar or other ranging techniques with ~10 cm accuracy is adequate). While shallower high-latitude snow, which is spatially extensive and important for global climate, can use an integrated measurement over a large footprint but needs precision in that mean variable (i.e. a 10 cm error is a large fraction of the total depth). Additionally, different techniques will work better/worse at different points in the annual snow cycle (see Figure 1), when physical processes impact the accuracy of the measurements. We need to invest in modeling and data-assimilation systems that are smart enough to ingest multiple data sources at different points in this cycle. We can capitalize on satellites launched for various other purposes to get energy balance data, but we need to have the modeling sophistication to ingest this data to get the evolution of snow correct. This section develops these ideas with specific reference to types of snow, instruments available to characterize them, and places where SnowEx can advance the community towards readiness for a spaceborne snow mission by filling in critical gaps in our understanding of snow remote sensing.

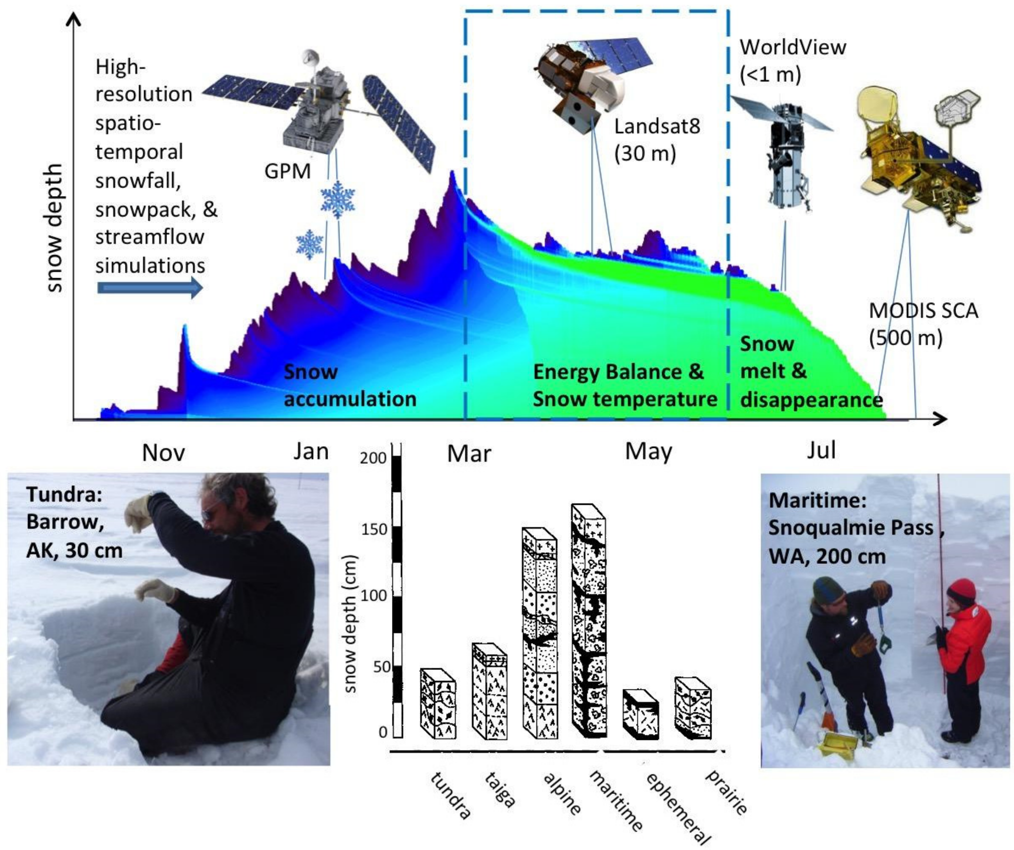

Figure 1. (top) Time evolution of snow mass (as represented with total snow depth) and snow energy (snow temperature, colors), and relevant existing spaceborne remote sensing platforms and spatial resolutions. (bottom) Snow climates from the Sturm et al. (1995) classification, with photos showing differences in snow depth in tundra and maritime snow. Figure courtesy of Jessica Lundquist.

In this section, we first detail recent progress in this field (§3.1). We then present a list of seven high-priority "gaps" in our knowledge of remote sensing of snow: these are areas where we believe focused airborne and *in situ* efforts could lead to improvement in our understanding of snow remote sensing, and ultimately support a spaceborne snow mission (§3.2). Finally we make recommendations for prioritizing SnowEx activities (§3.3).

3.1. Historical and recent progress on remote sensing of snow

Since the 1970s, much of Earth has been mapped for extent of snow cover (also known as snow-covered area, SCA or snow-covered fraction) largely based on instruments that work in the optical wavelengths. These data have led to tremendous discoveries about global-scale snow processes. For example, global snow cover mapping have revealed a sharp decline in June snow cover extent in recent years, and this rivals the late summer decline in Arctic sea ice extent [Derksen and Brown, 2012].

To date, only two global, space-based approaches for measuring SWE exist: passive microwaves and gravity. Gravity sensing, however, cannot meet our spatial resolution or SWE accuracy [TBC] needs, so we do not consider it further. Space-based passive microwave observations have been available for four decades, providing a long historical record, and empirical and semi-empirical methods have been developed to produce SWE estimates (Tedesco et al., 2006; Kelly, 2009; Chang et al, 1987). Alternatively, microwave emission models (e.g. Tan et al., 2015; Wiesmann and Matzler, 1999; Pulliainen et al., 1999) use physics-based approaches to simulate the effect of a snowpack on attenuation of the microwave radiation (Brucker et al., 2011; Durand and Liu, 2012; Kwon et al., 2015). Heritage passive microwave sensor footprint size was originally fairly coarse (dozens of km) and affected by multiple factors, including deep snow, liquid water content and vegetation (Ramage et al., 2007; Derksen et al., 2010), which significantly impact the accuracy of the snow estimation, particularly in regions with complex terrain. However, footprint size has steadily improved, and current state-of-the-art for snow channels is 10-15 km. Hardware-based technology for 5 km passive microwave footprints has existed for some time. And, recent software-based technology (Long and Brodzik, 2016) offers tools for resolution enhancement in post-processing beyond hardware technology limits; evaluating the accuracy of this should be an objective of future SnowExs.

Sensors and approaches for remote sensing of snow have been reviewed multiple times in recent years. Nolin (2010) reviewed methods for measuring snow cover, albedo, SWE. She highlighted that multi-sensor approaches are appealing for snow for overcoming limitations of individual sensors, and the challenging effects of forest canopies across all sensor types. Dietz et al. (2012) concurred with this assessment. Lettenmaier et al. (2015) included a section on snow in the review of remote sensing of hydrology. They highlighted the problem of direct measurement of mountain SWE from spaceborne platforms. All three review papers share a common consensus: mature technologies exist for mapping snow cover fraction, albedo, and surface temperature, but no existing technology has been proven as a candidate for global remote sensing of SWE that meets scientific requirements.

Here, we first review several recent spaceborne mission proposals based on rather more mature technologies, and then provide a survey of thirteen technologies for remote sensing of snow. These technologies span the TRL gamut from experimental to well-established methods.

3.1.1. Recent proposed SWE spaceborne missions

The societal benefits of a snow satellite mission are recognized as excellent and necessary. However the algorithm maturity in recent proposed missions has not been sufficiently rigorously demonstrated. The Cold Lands Processes Pathfinder (CLPP) mission was a NASA synthetic aperture radar (SAR) and passive microwave concept submitted to the 2007 Decadal Survey. It was recommended by the 2007 Decadal Survey. However, due to limited SAR algorithm maturity and other issues, it was listed as a so-called "third-tier" mission.

The Cold Regions Hydrology High-Resolution Observatory (CoReH2O, Rott et al., 2014) was a proposed European Space Agency snow SAR mission (Rott et al., 2010). This mission advanced to the "stage-of-three" downselect decision, where it competed (unsuccessfully) with missions to measure vegetation and atmosphere. The "no go" decision was based in part on the limitation that SWE could be reliably retrieved only where forest cover was less than 20%. The SWE retrieval algorithm also required high-precision *a priori* estimates of snow grain size. Thus, the SAR algorithm limitations remain an issue.

A dual frequency Ku-band radar mission entered phase 0 at the Canadian Space Agency in summer 2018. This technical concept provides 250-m resolution measurements at 13.5 and 17.2 GHz across a 500 km swath, with a stripmap mode (narrower swath) with 10 m resolution. Scientific activities, field campaigns, radar technology development, and programmatic options (including international partnerships) will be pursued during the next two years. This has been proposed to the European Space Agency under the Earth Explorer 10 mission call.

Water Cycle Observation Mission (WCOM) is an upcoming Chinese mission that will focus on soil moisture and sea salinity, SWE and soil freeze/thaw, plus precipitation/water vapor and ocean evaporation (Xiong et al., 2016; Shi, 2017). WCOM will include three instrument payloads: an interferometric radiometer (passive) operating at L, S, & C bands; a dual-frequency scatterometer (active) operating at X & Ku bands, and a real-aperture microwave radiometer (passive) operating at C/X/Ku/K/Ka/W bands (6-89 GHz). Reductions in mission scope are likely. For snow purposes, the scatterometer and the real-aperture radiometer are of interest. The scatterometer is expected to be wide swath (>1000 km), with 2-3 day repeat, and 2-5 km spatial resolution after processing. The choice of the 2nd frequency (14 or 17 GHz) is to be determined. Launch is anticipated in the mid-2020s.

The 2017 Decadal Survey to guide NASA missions through 2027 featured snow prominently. Specifically, the *SBG* VSWIR imaging spectrometer targets snow spectral albedo and its controls as one of its 5 Most Important measurements along with those from ecology and geology. Additionally, the *Snow Depth/SWE* "Earth System Explorer" concept to measure snow depth and snow water equivalent was also included in the Decadal Survey; radar and lidar were listed as possible technologies for this mission. The overriding top recommendation of the Water Panel is actually for an integrated earth system framework using satellite observations and models, spanning all parts of the water cycle, not just snow [*National Academies*, 2018]. In order to help achieve this integrated earth system framework with respect to snow, a global snow observation strategy is required. The Water Panel's recommended target observables include surface characteristics (albedo, temperature), SWE & snow depth, soil moisture, precipitation & clouds, terrestrial ecosystem structure, planetary boundary layer , aquatic biogeochemistry, surface deformation, and ice elevation. Although the Decadal Survey's Water Panel section lists snow observation requirements and suggests multiple potential measurement techniques (e.g., a GPM-style dual band Ka/Ku non-InSAR radar altimeter, or Ka band InSAR radar or lidar altimeter), the panel did not specify a single approach. Quantitative performance under different conditions is unknown, and this fact remains a mission proposal risk, and a strong argument for SnowEx's gap filling strategy to quantify the tradeoffs scientifically and rigorously. This will take time, and there will be pressure to jump to a specific solution to "save time," but we recognize that more scientific rigor is the best remedy to avoid a repeat of proposal immaturity. Parallel to this broad rigorous mapping of our "mission tradespace," focused efforts to evaluate the viability of specific concepts can be undertaken in response to specific mission Announcements of Opportunity.

3.1.2. Recent progress in airborne measurements of snow

In the past ten years, i.e., since the last decadal survey, progress on remote sensing of snow has proceeded for several technologies. Legacy techniques such as passive microwave have continued to advance, with numerous papers following on from the Canadian International Polar Year (e.g., Langlois et al., 2011) focusing specifically on the dominant role that forest cover plays in determining the passive microwave signal.

Significant progress has been made on the multi-frequency scatterometry approach, with significant datasets collected in 2006, 2007, and 2008 as part of the CLPX-2 campaign (Xu et al., 2010) and between 2007-2012 during airborne campaigns (e.g., SARAlps2007, NoSREx) in support the CoReH2O SAR concept. Rott et al. (2008) explored backscatter from radar data for mountain snow from a helicopter. Rott et al. (2014) collected scatterometry data in the Austrian Alps in the winter of 2012 and 2013. Radar measurements of tundra snow in Trail Valley Creek began in winter 2013 and 2014; more data will be collected in winter 2019.

In the past decade, lidar has emerged as an unprecedented means of accurately mapping snow depth (typically leveraged to estimate SWE) in mountain regions (Deems et al., 2013). Notably, this technique has been demonstrated since 2013 in select mountainous watersheds of the western United States through the NASA Airborne Snow Observatory (ASO), which measures snow depth from airborne lidar and snow albedo with an imaging spectrometer for integration into a snow model to map SWE for water cycle science as well as watershed operations and management. In a 2017 commentary, Lettenmaier (2017) highlighted the observational breakthroughs for hydrologic science along with drought monitoring.

3.1.3. iSWGR Survey of Snow Estimation Techniques : Quad Charts

As noted above, SnowEx activities will include a series of field and airborne experiments across multiple kinds of snow. While the primary variable of interest is SWE, we recognize the importance of measuring snow energy balance (viz. albedo, snow cover fraction and surface temperature), which enable understanding of changes in the thermal state of the snowpack. We also recognize that models and data assimilation for dataset merger is critical.

In 2014, the various techniques for estimating SWE, albedo, snow cover, and surface temperature were described in a series of quad charts developed by the iSWGR group that list the strengths and tradeoffs for each approach. These quad charts were presented and further developed at an iSWGR/SnowEx workshop in Longmont, CO in August 2017 (Appendix C) Categories for techniques are those that measure SWE via altimetry, via volume scattering, or via "volume-interometry" (where phase measurements are made from a radar signal that penetrates to the snow-soil interface) , and those that measure energy balance. Models are listed as a separate category.

We note here that while spaceborne gravimetry from GRACE can be used to infer total storage, it cannot directly parse out the individual mass balance components. Future versions of this document will review efforts to infer snow mass from GRACE.

SWE Retrieval via Snow Depth

- **Differential Lidar Altimetry** - Geodetic calculation of snow depth at high resolution in complex terrain and under forest canopies; SWE retrieval in combination with snow density modeling
- **Ka-band Interferometric SAR altimetry**– Differential repeat-pass interferometric phase measurements provide estimates of snow depth for dry to wet snow conditions; SWE retrieval in combination with snow density modeling
- **Stereo Photogrammetry** –Snow depth retrieval by differencing repeat high-res DEMs derived from satellite stereo imagery; structure from motion (SfM) is a form of stereo photogrammetry, appropriate for airborne applications; SWE retrieval in combination with snow density modeling
- **Wideband Autocorrelation Radiometry** – Passively measure microwave propagation time through a snowpack yields a direct measure of snow depth

SWE Retrieval via Volume Scattering

- **Multi-Frequency Ku-Band Radar Backscatter** - Measures volume scattering response of snow to retrieve snow water equivalent in dry snow conditions. Various combinations of bands are possible (e.g., dual K, X and Ku).
- **Multi-Frequency Passive Microwave** – Measures natural microwave emissions and volume scattering response in presence of snow; uses difference at multiple frequencies to retrieve snow water equivalent in dry snow conditions

SWE Retrieval via Volume-Interferometry

- **L-band interferometric SAR** – Differential repeat-pass interferometric phase measurements provide estimates of snow water equivalent (SWE) for dry to lightly wet (~6%) snow conditions
- **Signals of Opportunity** (SoOp)- Using reflected transmissions from sources such as GNSS and XM Radio waves to measure snow depth (for wet snow) and SWE (for dry snow).

We note here that the Decadal Survey proposed exploration of a new technology not in our quad charts or Tables: dual-band Ku/Ka non-SAR altimetry.

SWE Retrieval Confined to Airborne or Ground-based Platforms

- **Frequency Modulated Continuous Wave Radar** – Measurement of travel-time in snow gives estimates of SWE, snow depth, and stratigraphy
- **Gamma** – Differential gamma attenuation to map snow water equivalent over unvegetated surfaces

Snow Energy Balance and Extent Retrieval

- **Multispectral/Hyperspectral Imaging Spectrometry** - Hyperspectral measurement of reflected light to retrieve snow covered area, snow albedo, snow surface temperature, surface grain size, absorption by dust/soot/biological particulates, and surface liquid water content

Modeling

- **Physically-based Modeling –** Using physically-based principles and parameterizations to simulate snow accumulation, energy exchange, and melt; and wildlife-relevant properties such as depth and surface hardness.
- **Radiative Transfer Modeling** - Using electromagnetic theory and parameterizations to represent snow microstructure and represent scattering, extinction, and emission of microwave radiation
- **Data-driven Modeling** - Using statistical prediction models (e.g., regressions) or machine-learning algorithms to estimate SWE based on data collected from remote sensing and/or ground-based observations

Tables 1-3 are an attempt to map the techniques for estimating SWE, snow cover, /albedo, and surface temperature, described in the quad charts to identified gaps in snow estimation capabilities based on the strengths and challenges associated with each. In the tables, green indicates a demonstrated capability, which may not work in all conditions but uncertainty is fairly well understood. Yellow indicates a development opportunity, where a potential capability has been identified and validated in multiple studies, but uncertainty is not well quantified. Orange represents a new research area where a potential capability has been identified, but not well validated, and red represents a hard limitation for a particular technique that is unlikely to be overcome.

Table 1. Summary of snow depth/SWE and snow melt estimation techniques

		Snow Characteristic			Gap Capabilities							Space Potential		
Type	**Snow sensing/ estimation Technique**	**Snow Depth**	**SWE**	**Melt**	**High-Res**	**Wet snow**	**Deep Snow**	**Forests**	**Complex Terrain**	**Shallow Snow**	**Clouds**	**Path to Space**	**Global coverage**	**Mature Algorithm**
SWE via snow depth	Lidar	Green	Yellow	Red	Green	Green	Green	Yellow	Green	Yellow	Red	Green	Yellow	Green
	Ka-band InSAR	Green	Yellow	Red	Green	Green	Orange	Red	Green	Orange	Orange	Orange	Orange	Orange
	Dual band Ku/Ka	Green	Yellow	Red	Green	Green	Green	Red	Orange	Orange	Green	Orange	Orange	Orange
	Stereo Photogrammetry	Green	Yellow	Red	Green	Green	Green	Orange	Green	Orange	Red	Green	Yellow	Green
	Wideband Radiometer	Green	Yellow	Red	Orange	Red	Orange	Orange	Orange	Orange	Green	Orange	Orange	Orange
volume scattering	Ku-band SAR	Yellow	Green	Green	Green	Red	Yellow	Orange	Orange	Yellow	Green	Yellow	Yellow	Yellow
	Passive Microwave	Green	Green	Yellow	Orange	Red	Red	Orange	Yellow	Green	Green	Green	Green	Green
signal interferom.	L-Band InSAR	Yellow	Green	Green	Green	Red	Yellow	Orange	Orange	Yellow	Green	Green	Yellow	Yellow
	Signals of Opportunity	Yellow	Yellow	Red	Orange	Yellow	Orange	Orange	Orange	Orange	Orange	Orange	Orange	Orange
airborne / ground only	FMCW Radar	Green	Green	Red	Green	Yellow	Green	Orange	Orange	Green	Green	Red	Red	Orange
	Gamma	Yellow	Green	Red	Yellow	Green	Yellow	Yellow	Yellow	Yellow	Green	Red	Red	Green

Green – Demonstrated capability. May not work in all areas, but uncertainty is understood. May still benefit from additional research and algorithm development. TRL > 5?

Yellow – Potential capability identified and validated in multiple studies. Research needed to better quantify uncertainty. TRL 3-5?

Orange – Potential capability identified, but uncertainty not quantified. High risk. TRL 1-2?

Red – No Capability

Table 2. Summary of snow energy and extent estimation techniques

	Snow Characteristic			Gap Capabilities							Space Potential		
Snow sensing/ estimation Technique	**Albedo**	**Thermal IR**	**SCA**	**High-Res**	**Wet snow**	**Deep Snow**	**Forests**	**Complex Terrain**	**Shallow Snow**	**Clouds**	**Path to Space**	**Global coverage**	**Mature Algorithm**
Hyperspectral	Green	Green	Green	Green	Green	Green	Orange	Yellow	Yellow	Red	Green	Green	Green
Multispectral	Green	Green	Green	Green	Green	Green	Orange	Yellow	Yellow	Red	Green	Green	Green

Green – Demonstrated capability. May not work in all areas, but uncertainty is understood. May still benefit from additional research and algorithm development. TRL > 5?

Yellow – Potential capability identified and validated in multiple studies. Research needed to better quantify uncertainty. TRL 3-5?

Orange – Potential capability identified, but uncertainty not quantified. High risk. TRL 1-2?

Red – No Capability

Table 3. Summary of snow modeling techniques

	Snow Characteristic			Gap Capabilities							Application Potential	
Snow sensing/ estimation Technique	**Snow Depth**	**SWE**	**Melt**	**High- Res**	**Wet snow**	**Deep Snow**	**Forests**	**Complex Terrain**	**Shallow Snow**	**Clouds**	**Global coverage**	**Mature Algorithm**
Physical Modeling	Green	Green	Yellow	Green	Yellow	Green	Yellow	Green	Green	Green	Green	Green
Radiative Transfer Modeling	Green	Green	Orange	Green	Orange	Orange	Orange	Orange	Yellow	Orange	Green	Orange
Data-driven Modeling	Green	Green	Orange	Green	Orange	Orange	Orange	Orange	Orange	Orange	Green	Orange

Green – Demonstrated capability. May not work in all areas, but uncertainty is understood. May still benefit from additional research and algorithm development. TRL > 5?

Yellow – Potential capability identified and validated in multiple studies. Research needed to better quantify uncertainty. TRL 3-5?

Orange – Potential capability identified, but uncertainty not quantified. High risk. TRL 1-2?

Red – No Capability

3.1.4. Potential multi-sensor synergies, tradeoffs, and data assimilation

Based on the literature, prior airborne/field campaigns, and expert guidance, there are multiple opportunities for a multi-sensor approach that could permit mapping of SWE with global capabilities. A non-exhaustive review of potential synergies and tradeoffs follows. These approaches (among others) should be assessed in the design of SnowEx field campaigns.

One approach would include a sensor that measures snow depth (e.g., via altimetry) and combines that with modeled snow density to map SWE. This concept has been demonstrated in recent airborne campaigns, such as ASO (Painter et al., 2016). If only a single high-resolution sensor were selected, there is an apparent tradeoff in capability with respect to clouds (which restrict lidar and stereo photogrammetry) and forests (which respect application of Ka-band InSAR and dual band Ku/Ka), as seen in Table 1. Pairing two of these sensors could enable complementary mapping of snow depth in a range of locations as long as forests and cloud cover (long-standing challenges to snow remote sensing) are not simultaneously present. It is possible to map snow depth with single sensors that are insensitive to clouds (e.g., dual band Ku/Ka and wideband radiometry), but the SWE retrievals may be limited for shallow snow, and snow in complex terrain and moderate-to-high density forests. Wideband radiometery may have additional limitations in areas with deep snow and may not yield high resolution information. Validated physically-based snow models could provide the estimated snow density to support mapping of SWE with any of these snow depth sensors, and could be further supported through assimilation of snow density estimates, which may be possible under dry snow conditions with L-band radars (e.g., Shi and Dozier, 2000).

Another multi-instrument approach is including one sensor for mapping snow in complex terrain at a higher resolution and a second sensor for mapping snow in areas where such fine resolution is not as important. This could be crucial for achieving global coverage as swath width tends to be inversely proportional to resolution. In this case, the high-resolution capacity might be supported by sensors such as lidar, dual-band Ku/Ka, or stereo photogrammetry, while the coarser-resolution capacity might be supported by sensors such as a wideband radiometer or a traditional passive microwave sensor (Table 1). Snow density would still be required to map SWE with the high resolution sensor, which could come from modeling, a third sensor (L-band), or possibly from the coarser-resolution sensor (e.g., passive microwave). This multi-sensor approach would be similar in concept to the Chinese WCOM mission, which proposes a dual band (Ku and X) SAR at moderate resolution (2-5 km), a multi-band passive microwave instrument at moderate-to-coarse resolution (4-50 km), and an interferometric radiometer (L-band passive) which could provide an independent retrieval of snow density. The multi-frequency capability of radars could also be leveraged to provide high-resolution and coarser resolution mapping of snow; this strategy is being pursued in the dual Ku-band proposal to the Canadian Space Agency.

A final specific example of a multi-scale, multi-sensor approach is one that combines a radiometer (passive) with a radar (active), similar to past mission concepts for snow (e.g., SCLP) and soil moisture (e.g., SMAP). Alternatively, a SAR sensor (e.g., multi-band Ku) could be used to downscale or evaluate SWE retrievals from existing spaceborne passive microwave radiometers, and map areas of wet and dry snow, all capabilities identified in the CoReH2O proposal (Rott et al., 2010), and essentially the approach used by the Soil Moisture Active Passive (SMAP) mission. Multi-band Ku SAR and passive radiometers have similar capabilities and limitations in terms of SWE mapping, and hence this approach would have difficulty overcoming certain confounding factors (e.g., SWE retrievals in wet snow or deep snow) but in other environments (e.g., shallow snow) could yield unique data to improve understanding of scaling relationships in SWE.

Assimilation of variables related to snow extent and the surface energy balance provides additional synergy between remote sensing observations. Snow extent mapping from an imaging spectrometer provides useful context for retrieving SWE with passive radiometers. Assimilation of remotely sensed snow extent, albedo, snow surface temperature, and snow depth, into physically-based snow models may in turn improve estimation of critical variables required for SWE retrieval (i.e., snow density) and predictions of snowmelt (i.e., decreases in SWE).

3.2. Outstanding gaps

One of the goals of this document is to identify “gaps” in snow science and in our understanding of snow remote sensing. We are fundamentally motivated by gaps in snow science to address the most important unanswered snow science questions: most saliently, what is the global SWE throughout the season, how does snow contribute to the global energy balance, and how is global snow changing over time? At a more immediate level, we are motivated by gaps in measurement science as it applies to snow remote sensing--i.e., what are the most important unanswered questions in how our various sensors can measure SWE? How can we use established measurement sensors that provide snow cover, albedo and surface temperature with SWE measurements and models to better constrain SWE evolution? How can we measure and model snowpack characteristics at scales that are relevant to terrestrial ecology and wildlife management? The snow science and measurement science questions are interdependent. In this section, we prioritize exploration of measurement techniques that have the greatest potential to advance snow science. Furthermore, to align ourselves with the scope of the SnowEx activities, we additionally focus on those topics that can be addressed with a focused airborne and in situ field campaign.

The community consensus is that there is no “universal” solution for mapping global SWE —i.e, no single sensor measures SWE adequately across the large range of global snow conditions. However, by dividing the world’s snow covers into different types, we can match the appropriate tools to each snow type and confounding factor. The vast area of snow can be subdivided into snow on sea ice (e.g. Sturm and Massom, 2010), perennial snow on glaciers and ice sheets (e.g. Benson, 1969; Cuffey and Paterson, 2010), and seasonal terrestrial snow, which has been further subdivided into 6 classes by Sturm et al. (1995) and Liston (2004). The various snow classes take into account the wind, precipitation, and temperature regimes these snow covers evolve within, and that depth, density, number of layers, grain characteristics, metamorphic trajectories and melt sequences differ across these various types of snow. Each snow type contributes in an important way to the hydrology and climatology of the Earth. Additionally, the societal significance of snow cover is different in the various classes. For example, mountain snow cover is a major contributor to water resources in many areas of the world; winter recreation and tourism is also important in alpine areas. Prairie snow cover is important for crops and animals (grazing, etc.), while ephemeral snow cover often severely impacts transportation and thus safety. Tundra and taiga snow, while having a less obvious and direct influence on humans, greatly influence weather due to their spatial extent, higher albedo and lower thermal conductivity. Our challenge is to bring to mature remote sensing of snow to these snow climate classes. Considering two extremes, dry tundra snow covers 16.5 million km^2 but is only 0.3-0.5 m deep, while wet maritime snow covers only 3.6 million km^2 but is much deeper (1.5-2.0 m). These very different snow types, which require very different sensing approaches, contain a similar geometric volume of total snow (~5,000-8,000 km^3) and are both critical to global energy balance and water supplies. Independent technologies exist for both of these regions, but they transfer between regions poorly.

We identify seven gaps that represent breaks in the continuity of our knowledge of seasonal terrestrial SWE remote sensing techniques that have great relevance for advancing global snow science and, if addressed, could ultimately lead to a spaceborne snow mission concept. In addition, techniques found to improve seasonal terrestrial snow estimation have the potential to advance estimation of snow on sea ice, and perennial snow on glaciers and ice sheets. These gaps, that could be filled with a focused airborne and field campaign, are:

1. Forest snow
2. Mountain snow
3. Tundra snow
4. Prairie snow
5. Maritime snow
6. Snow surface energetics
7. Wet snow

Forest Snow: An estimated area of four million km^2 of forest in the mid-latitudes and 11 million km^2 of boreal forest (i.e. higher latitudes) is impacted by seasonal snow, which plays a crucial role in global biogeochemical and ecological cycles. Our ability to measure snow in forests has been limited because existing remote sensing technologies cannot fully see snow through tree canopies and masking effects of tall vegetation makes it difficult to quantify the albedo and surface temperatures. Newer sensing techniques have unquantified accuracy under forest conditions.

Mountain Snow: Mountain snow acts as a natural reservoir where water during the cold season is retained and later released as snowmelt. Mountainous areas provide disproportionately more streamflow than corresponding lowland areas downstream [Viviroli et al., 2007], and in many mountain ranges globally the majority of precipitation falls as snow. The primary challenges of measuring snow in mountains include deep snow, high spatial variability, and topographic shading. Physical processes that govern snowpack mass and energy balance in mountains can vary over multiple length scales, depending on gradients in elevation, slope, and aspect. In that sense, mountains may be considered a special subset of topographic complexity.

Tundra Snow: Tundra is the most representative biome of arctic land regions underlain by permafrost, covering ~8 million square km (~5.4% of the land surface of the earth vs. 7% for boreal forest). Warming promotes thawing of permafrost which affects the hydrology of the arctic through a deeper active layer (the upper portion of the tundra and permafrost which thaws during the summer), increased soil moisture storage, warmer soil temperatures, increased evaporation, and release of long-sequestered carbon. Tundra snow also affects iconic wildlife such as caribou and Dall sheep who depend on adequate winter forageable area and shallow snow for migration. The snow measurement challenge in tundra areas is tied to the relatively thin snowpack (<1m depth, and 0.35m is typical), huge metamorphic changes inside the pack over the winter (due to thermal gradients >100K/m) cause large contrasts in snow microstructure, and a rapid melt (e.g, 1 week).

Prairie Snow: Prairie and tundra cover over 16 million square kilometers, or about 10 percent of the land surface area of the planet. Prairie snowpack is generally shallow, and microwave observations have shown promise. However the subsurface characteristics (e.g. soil moisture, vegetation) can significantly impact the signal. As this snow climate is generally mid-latitude, lower elevation, and generally warmer, wet snow is also an issue, especially in fall and spring.

Maritime Snow: Maritime snow covers over 3.6 million square kilometers, and provides a significant source of water to coastline areas. Snow in these regions is generally deep, and often wet due to rain-on-snow and warmer convective events. Remote sensing techniques are also affected by vegetation and the common occurrence of cloud cover in these areas. In part due to the challenge of wet snow and maturity of techniques, maritime snow has received less attention during previous snow remote sensing efforts.

Snow Surface Energetics: Understanding changes in SWE over short (hourly-seasonal) and long (annual-decadal) time scales requires accurate assessment of the snowmelt energy balance. Remote sensing can provide insights into the thermal state (via snow surface temperature from IR sensing) and melt state (via albedo from spectral imaging spectrometry) of snowpack. In some regions (e.g., very cold snow zones), it is possible that climate warming may be manifested in changes in the snow surface energetics years or decades before changes can be detected in the form of declining SWE. The snow surface temperature and albedo are physically linked, as temperature is one factor controlling snow grain growth, and reduced albedo increases snow temperature (or can cause snowmelt once at the melting point). Reductions to land surface albedo - due to loss of seasonal snow and/or decay of snow albedo - has important consequences to global climate through albedo feedback. Air temperature projections using the current global circulation models are challenging especially in forested and mountainous regions due to large uncertainties associated with snow albedo feedback. There is a pressing need to obtain high quality observations of snow surface albedo in these regions, but landscape heterogeneity complicates our efforts. There are also challenges associated with representativeness of either ground-based, airborne or satellite albedo measurements (Román et al., 2009; 2011; Wang et al., 2014), with the angular dependence of both sun and sensor further challenging accurate retrievals.

Wet Snow: The spring snowmelt period is a critical time for monitoring snow for both water resources and flood forecasting. An accurate estimate of the snowmelt magnitude and the timing of melt runoff is important for water management, however many remote sensing techniques cannot “see” through wet snow. Furthermore, altimetry and differencing methods require an estimate of snow density to convert depth to SWE often obtained from models, however the spring melt period is also when most model uncertainty is high (Essery et al. 2013). These measurement challenges are further exacerbated in maritime snow and snow in transitional zones which can experience wet snow throughout the winter season due to rain on snow or melt events.

3.3. Defining Priorities for SnowEx Activities

In §3.1 and §3.2, we reviewed the science of remote sensing of snow, ongoing efforts at a snow mission, and quad charts (Appendix C) of technologies for snow remote sensing and estimation (§3.1). We have then detailed seven scientifically-relevant gaps in our knowledge of snow remote sensing (§3.2). The aim of all of this has been to prioritize SnowEx activities. In this subsection we propose prioritization of SnowEx activities, and provide a preliminary a strategy to address the identified gaps.

Objectively prioritizing these gaps is challenging. Each of the seven gaps has global importance. What criteria should be used for prioritization? One option is to assess the long-term average maximum global spatial extent of each of these types or conditions of snowpack; this is possible for most gaps with the Sturm et al. (1995) classification. Under this framework, one might consider the type of snow that covers the most area to be most important. A second option would be to assess the long-term average maximum global volume (i.e. the spatial integral of long-term average maximum SWE over its extent) of each type; this is far more problematic, however, due to large uncertainties e.g. in mountain snow in existing global datasets (e.g. Wrzesien et al., 2018). Indeed, there is a bit of a catch-22 or a “chicken-or-egg” problem here. We want to motivate spaceborne mission to study global snow using accurate estimates of how much global snow is stored in each snow type; but we cannot estimate how much snow volume is stored in each snow type without the global snow mission. Additionally, algorithm and technological readiness (both current and anticipated near-term) is a valid criterion for prioritizing SnowEx activities. Field campaigns are key to validating algorithms and improving our understanding of temporal and spatial mission requirements, all of which play a role in readiness decisions for SnowEx activities.rA final set of possible criteria is the socio-economic, socio-cultural, and ecological, values of snow. Determining how to objectively weight these criteria is yet another challenge.. Here we take a pragmatic, while admittedly somewhat subjective approach, and point the way to future activities to make such prioritizations more objective.

3.3.1. Addressing gaps with SnowEx field campaigns

As a start towards selecting potential campaign sites and prioritizing the SnowEx activities, we recognize that there is overlap among the gaps, in that many exist concurrently and could be addressed simultaneously. For instance, a field campaign in the mid-latitude mountains would likely address deep snow in complex terrain and potentially the impacts of forests as well. Similarly, another in a high-latitude low topography region may address shallow snow challenges that impact tundra and prairie measurement capabilities. Before we describe potential future campaigns, we asked what gaps have already been partly addressed by SnowEx 2017, and what might be addressed by the planned SnowEx 2019 campaign, and the proposed 2020 campaign collaborating with ABoVE. While the motivation underlying the "forest" gap is certainly still relevant, the 2017 dataset is still being explored and analyzed. We propose that while future campaigns will likely focus on other remote sensing gaps, the ability to sense SWE under forest canopies is still of great concern; note the lack of techniques with demonstrated capabilities in forests in Table 1. Thus, we recommend that future SnowEx campaigns should (to the extent possible) make measurements that span gradients in forest cover, towards addressing their goals, e.g. Mission Objective 1 for the SnowEx 2019 campaign is *Quantify snow mass and physical properties across topographic and vegetation gradients in different snow environments*, and the 2019 fundamental question is: "*What are the physical controls and dynamics of accumulation and melt of seasonal snow (SWE) across topographic gradients?"* Vegetation remains big piece of this puzzle, especially below treeline in montane environments and in the Arctic boreal region; indeed, trees are still very much in view.

SnowEx 2019: A major focus of the proposed SnowEx 2019 is mountain snow, during both the accumulation and melt periods, and therefore experiments will target gaps 2,3, and 7, as these observations will include the mountain, maritime, and wet snow climates (SnowEx 2019 Implementation Plan). Because SnowEx 2019 may be the only campaign with the opportunity to investigate SWE retrievals for maritime snow, the science plan recommends that campaign design and implementation provide due consideration to this specific snow zone, in addition to mountains and wet snow. This may necessitate reprioritization to consider study areas on the west slope of the central or northern Sierra Nevada. Prairie, warm forest, and taiga snow climates are also within the three Regional Study Areas (RSAs) that are currently under consideration by the Implementation Team. These RSAs include well-instrumented and gauged hydrologic basins, comprehensive snow mass and energy balance observations, and contain locations of currently planned 2018-19 airborne activities. The three RSAs are located in California, Colorado, and Idaho; specific locations of field operations and flight lines are still TBD, and will be guided by preliminary results from the ongoing Observing System Simulation Experiment (OSSE). The OSSE is aimed at highlighting priority areas of snow estimation uncertainty and analyzing snowfall frequency to help determine temporal resolution of the airborne and field based experiments. Exact locations of focus areas within these RSAs will be determined based on available resources, and by leveraging existing and planned remote sensing data. During 2019, Environment Canada, funded by the Canadian Space Agency, will be making field and airborne measurements of tundra snow in Trail Valley Creek, Canada. An airborne Ku-band SAR will fly this site approximately monthly, starting in October, and there will be a field team of 12 scientists performing calibration / validation observations in March 2019.

NASA will likely contribute to this effort by including an overflight by the Operation IceBridge P-3 instrument suite. See the SnowEx 2019 Implementation Plan for more details.

SnowEx 2020: A third campaign is centered on measuring snow at high-latitudes, including boreal forests and arctic tundra. A campaign for this snow type has great potential for synergy with ongoing NASA Arctic Boreal Vulnerability Experiment (ABoVE) activities , based on the Field Campaign Notes document (link). Gaps related to forest snow, snow energetics, (e.g., snow albedo feedback, and tundra (gaps 1, 5, and 6) are important in high-latitude regions. This focus on snow in the Arctic boreal region will provide an opportunity to assess whether results over temperate coniferous forests in the prior campaigns (2017, 2019) are valid in higher latitude cold forests, where forest structure and surface processes are different. Given the similarity between tundra and cold prairies (e.g., shallow snow over flat, unforested terrain), the science plan recommends particular attention be given to whether SWE retrievals over tundra are transferable to prairies. This may require expansion of the study domain beyond the ABoVE study area. While prairie snow may be a great distance from the ABoVE study area (Figure 1), an innovative implementation might consider airborne surveys over cold prairies while in transit to the ABoVE study sites. The science plan also notes that the ABoVE domain may offer opportunities to obtain airborne microwave data (radar volume scattering approach and passive microwave) that were not well represented in the SnowEx 2017 airborne dataset.

SnowEx 2021: A fourth potential campaign will focus on the remaining outstanding gaps. By the end of SnowEx 2020, we project that due attention will have been given to forests (SnowEx 2017, 2019, 2020), mountains (SnowEx 2017, 2019), tundra (SnowEx 2020), snow energetics (SnowEx 2017, 2020), and wet snow through a time series campaign (SnowEx 2019). The remaining gaps that are candidates for a final campaign in 2021 are prairie snow and maritime snow. There may be opportunities to make progress on these gaps in SnowEx 2019 (maritime snow in the Sierra Nevada) and SnowEx 2020 (shallow snow), however the expectation is that these are secondary foci (to mountains in 2019 and to boreal snow in 2020). The science plan suggests two possible focus areas for a campaign in 2021 (below), and recommends ongoing discussion with the implementation team of that campaign to weigh the results from prior SnowEx campaigns and other community efforts when designing the 2021 campaign.

- ***A prairie snow focus*** - A campaign focusing primarily on prairies would address a globally extensive snow zone that has notable climate importance and huge importance to global agriculture, flooding, etc, thereby making for a more strongly motivated proposal for a future spaceborne snow mission. The lack of a concentrated effort over prairies may be a proposal risk, and therefore it is important to quantify SWE retrieval accuracy in this zone. It is unclear whether the uncertainty in snow retrievals over shallow snow over other snow climates (e.g., tundra) is representative of snow retrievals over shallow snow in prairies. For microwave techniques in particular, an important consideration is differences in substrate (e.g., soil minerals, organic matter, permafrost) and water content, and these may vary between prairies and tundra. There are a small handful of accuracy assessments of passive microwave retrievals at the footprint scale from Derksen et al (2003, 2004) and Goodison et al (1984), and CLPX-1, but it is not known how the accuracy of other techniques (e.g., SWE from snow depth from altimetry) compare to passive microwave sensing in prairies. A notional study area for a prairie SnowEx campaign in 2021 is the region in the vicinity of the Red River of the North (Fig. ES1f), which has a history of snowmelt generated floods.

- ***A maritime gradient spanning a range of conditions*** - A campaign focusing on a gradient of maritime influence at mid-latitudes would address a snow zone that provides water to many population centers worldwide. The maritime snow zone is characterized by a different energy balance regime (e.g., more prominent longwave radiation), persistent clouds, wet snow, deep snow, and (in some regions) dense forests. The latter factors are well-known issues for snow remote sensing. The inclusion of multiple confounding factors in a maritime climate would be a departure from the SnowEx general strategy of isolating confounding factors (see §4.2), but at the same time this might reveal the upper error limit for sensors in what may be the most challenging snow remote sensing environment. The SnowEx strategy for varying a confounding factor could still be preserved by choosing airborne routes and field studies in a transect perpendicular to the nearest ocean. A notional study area for such a maritime campaign is the Pacific Northwest (Fig. ES1e), where a longitudinal transect would capture snow in two maritime mountain ranges (the Olympics and Cascades), ephemeral snow in between, and prairie snow on the Columbia Plateau (east of the Cascades). This particular study area could leverage data collected from the NASA OLYMPEX campaign (2015-2016), which included airborne lidar surveys from ASO.

3.3.2. A Proposal for Prioritizing SnowEx Activities

Given the available sensors, existing gaps, and tentative mapping of gaps onto field campaigns, this section makes a proposal for prioritizing SnowEx activities. We define “activities” as testing a particular snow estimation technique or sensor (detailed in §3.1.2) in a particular gap (detailed in §3.2). Given our objective to support a global SWE measuring mission, we prioritized testing sensors with a path to space (see Table 1). Given the Decadal Survey promotion of the SBG mission, and the need to constrain snow energy along with mass balance, and the need to combine information across sensors, we prioritize snow cover, albedo, and TIR measurements, along with modeling and data assimilation. Activities break down into four qualitative categories: mission critical, crucial, important, and beneficial. Note that field campaigns to validate these measurements are mission critical. We want to stress that if resources are available, all sensors ought to be flown in all campaigns, including legacy and newer sensors. The snow community has not yet settled on a particular sensor or combination of sensors, so having them all is ideal. Understanding that resources are not infinite, the priorities here provide a starting point for the implementation team in decision-making and planning campaigns.

We do not list all field observations needed to validate each sensor; this is left to the implementation team. In most cases, we list gaps that may be partially filled with the SnowEx 2017 data (details presented in Appendix B); we will leave to the implementation team whether new data are needed or not. We find that the following are the **mission-critical** SnowEx activities to address gaps in our knowledge of remote sensing, as relates to developing a future spaceborne mission:

- The most important gap in maturing multi-frequency Ku-band radar retrievals (volume scattering approach) are related to the ability to deal properly with the background, i.e. soils and submerged vegetation. This is documented in the writeups on the tundra and prairie snow gaps, in Appendix A. This is the focus of one THP17 project (P.I. Kang, et al) as well as in the international community: SnowEx efforts must dovetail with ongoing efforts by Canadians, Europeans and others to advance radar algorithms, to ensure that work is complementary, not duplicative. While these are challenging contexts, there is reason to believe that datasets may yield useful information (see Appendix A). Note that the input data for the background adjustment comes from passive microwave. So, passive microwave becomes a required measurement to make this radar retrieval work (which would inherently elevate the prioritization for passive microwave).
- The fundamental gaps related to the L-band InSAR technique are related to phase ambiguities and decorrelation, which affect all interferometric observations. These relate to all types of snow, and thus are relevant for all gaps. Top priority issues include the need to understand L-band in the context of forest cover: it is possible to penetrate forest cover at L-band, but it is not known how forest density leads to decorrelation, and ultimately how SWE retrieval accuracy is impacted. Understanding L-band performance in mountainous terrain is an important stress test for the ability to perform phase unwrapping. Field data appear to indicate that L-band still achieves penetration of wet snow in the presence of liquid water, but this must be further demonstrated using airborne data.
- Key areas for exploring the Ka-band InSAR technique are the challenge of unwrapping in steep terrain, interaction with vegetation and forest cover, and penetration depth. Previous airborne measurements have demonstrated robust performance in steep, mountainous terrain, but analysis of the performance with respect to topographic relief and viewing aspect should be further characterized. It is not expected to be able to measure snow depth beneath forest cover. The Ka-band InSAR technique is intended to be a surface measurement and penetration into the snow is considered a bias. Preliminary models for penetration depth should be calibrated and validated under SnowEx for varying conditions. For example, microwave models as well as passive microwave experience predict up to 1 m penetration in dry snow.
- We must include efforts to advance snow modeling and data assimilation activities as part of SnowEx, so that we can continue to explore how integrated use of these observations together, rather than in isolation, can help to address snow observation challenges. Gaps that need to be addressed include an assessment of uncertainty in modeled physical processes, spatial gap-filling capabilities for narrow-swath sensors (all our radar and lidar techniques), and advancement of assimilation techniques that take advantage of multi-scale remote sensing and in situ observations to characterize snow.
- Given the currently ability of airborne LiDAR to measure snow depth (and our only technique proven to work in forests, Table 1), it is crucial that these observations are part of SnowEx activities. This is all the more so, with the near-future launches of GEDI and IceSat-2. We have listed it here as "mission critical" as it is most likely going to be needed for validating the other sensors. Plus--as with all our high-resolution/narrow

swath techniques--spaceborne lidar in conjunction with models to provide spatial gap-filling is part of our candidate toolkit to map global SWE.

It is increasingly clear that single-sensor techniques in isolation are not likely adequate to understand global snow processes. It is **crucial** that the performance of these techniques be well-quantified through SnowEx activities as well so that we can begin to explore how using these datastreams (which would most likely be available during a future global snow satellite mission) can be used with the other techniques including modeling and data assimilation.

- Passive microwave sensors are legacy instruments that have shown sensitivity to snow mass and can help interpret newer measurements. These measurements are required to help understand the multi-frequency Ku-band radar volume scattering data: Many (but not all) of the physics are the same, but passive is better understood. Only limited footprint-scale accuracy assessments exist for passive microwave SWE retrieval, despite it being the only existing spaceborne approach for mapping SWE with near daily global coverage. It is crucial to have this as part of the SnowEx suite. When used successfully in combination with other critical measurements (e.g., multi-frequency Ku-band radar), and as a constraint for models, the importance of passive microwave data may become more elevated.
- Given the likelihood of the Decadal Survey hyperspectral imaging mission (SBG), and the importance of albedo to understanding snow processes, it is crucial that these observations be made as part of ongoing SnowEx activities. Albedo measurements provide valuable information about snowmelt, and thus have high potential to improve SWE monitoring and forecasting in models via assimilation. In turn, mapping of snow depth has potential to add context to the hyperspectral imaging mission, as relative contributions of snow and the underlying substrate to surface albedo can vary with snow depth (e.g., the substrate has greater influence on surface albedo in areas with shallow snowpack vs. deeper snowpack).
- Similarly, thermal-IR imaging of surface temperature is a mature technology with great value for characterizing snowpack energy state, and will be measured by SBG; TIR is especially crucial in maritime snow that is often close to the melting point.

It is **important** to include some instruments with less history of snow-specific measurements; however, we have only included them in this category if they have some history of airborne or spaceborne deployment.

- Photogrammetric methods have potential to be transformative technology. While estimates of elevations from platforms such as WorldView are of a high maturity, application to snow depth is non-trivial, and is thus a bit outside the acceptable maturity level. However, it is important to include these because of their immense possible value.
- Airborne FMCW measurements allow for inference of snowpack stratigraphy, and are thus important as well, even if no path to space currently exists.

It would be **beneficial** to include the additional technologies from §3.3.1 as resources are available.

- It is not clear that gamma sensing would provide a unique piece of information helpful for validating or understanding the mission critical observations, and it does not have a path to space. However, gamma does have a long record of operational use in NOAA’s National Operational Hydrologic Remote Sensing Center’s (NOHRSC) airborne survey program, and they have expressed interest in participating in SnowEx activities.

- SoOP sensors measure reflected signals from existing spaceborne missions have not (to our knowledge) been deployed on aircraft. It would be beneficial to include this, though it is still relatively low TRL.

- The autocorrelation radiometer has thus far been tested only in situ (to our knowledge). It would be beneficial to include this, though the technological readiness level (TRL) remains low.

- Snow density retrieval has been demonstrated by Lemmetyinen et al. (2016) and Naderpour et al. (2017) using ground-based L-band passive microwave measurements. Since this sensor type may continue to be available in space, and since density is required for SWE retrievals based on altimetry approaches, an airborne test would be beneficial. *Note: This technology is not included in our quad charts, but will be added in the future.*

3.3.3. Future work: Using the Snow Ensemble Uncertainty Project to work towards a more objective prioritization

The Snow Ensemble Uncertainty Project (SEUP) is a modeling exercise aimed at identifying regions of uncertainty in snow estimation based on the current state of modeling snow and cold season processes. The objective of this exercise is to support NASA's SnowEx by helping to select potential field campaign locations in regions where our current sensing capabilities could be improved. In addition, this project aims to begin quantifying snow estimation uncertainty across a range of snow classes, terrain and vegetation types. An initial analysis produced an ensemble of land surface model results over a North American domain at a 5 km resolution during the time period, 2010-2017, to focus on addressing the following science questions:

- What areas have higher SWE uncertainty across the ensemble?
- What areas have higher spatial and temporal SWE variability?
- Which landscapes have the largest snow mass and energy implications?
- What percentage of the water cycle involves snow?
- What is the distribution of SWE in different vegetation and terrain types?
- How does the uncertainty in the snow fields contribute to the uncertainty in snow melt and river runoff?

A future analysis will include high-resolution observing system simulation experiments (OSSE) over smaller sub-domains, aimed at quantifying the ability of various sensing technologies, model physics and assimilation techniques to improve snow estimation capabilities. This exercise will help test a framework for snow estimation that includes a combination of models and remotely sensed observations, as well as test techniques to merge data from multiple platforms and scales. This analysis could also help further prioritize SnowEx activities for future campaigns and will provide quantifications on the utility of future remote sensing snow observations to applications of water availability.

4. Science Plan

4.1. SnowEx Science Traceability Matrix

The science traceability matrix (STM) developed for SnowEx identifies mission objectives and ancillary questions, mission requirements, and data deliverables that will help address the overarching and fundamental questions. The STM was developed after the 2016-2017 SnowEx campaign and was based on science questions and requirements articulated by the wider community at prior workshops (e.g., SnowEx, iSWGR) and in the recent Decadal Survey, as well as motivating questions and outcomes of the first SnowEx campaign. A catalog of community-identified questions was compiled and rated by the NASA THP-16 investigators in regards to perceived importance to SnowEx. This was the basis for the overarching and fundamental questions in the STM. The set of four Mission Objectives/Ancillary Questions (column 1 in STM) derive from the two fundamental questions, and include subcomponents to address gaps in our knowledge of state variables, fluxes, physical processes, and measurement techniques. The measurement requirements, instrument functional requirements, investigation functional requirements, and data deliverables (columns 2-4 in STM) were originally articulated in the SnowEx 2016-2017 STM and maintain relevance to the multi-year campaign. The intent of the developed STM is to provide fundamental science questions and associated mission objectives and ancillary questions that are specific and granular enough to support campaign-scale planning, yet also have sufficient scope and diversity to enable multiple years of SnowEx scoping and implementation, depending on resource availability, PI participation, and instrument development and application, among other factors.

<table>
<tr><td colspan="5">SnowEx Overarching Question: What is the distribution of snow-water equivalent (SWE), and the snow energy balance, in different canopy types and densities, and terrain?</td></tr>
<tr><td rowspan="2">Fundamental Questions</td><td colspan="4">Q1 – What are the physical controls and dynamics of accumulation and melt of seasonal snow (SWE) across topographic gradients?</td></tr>
<tr><td colspan="4">Q2 – What are the patterns of snow accumulation and melt in boreal vs. temperate forests, and what is the resulting hydrologic partitioning of snowmelt in these areas?</td></tr>
<tr><th>Mission Objective and Associated Ancillary Questions</th><th>Measurement Requirements</th><th>Instrument Functional Requirements</th><th>Investigation Functional Requirements</th><th>Data Deliverables</th></tr>
<tr><td>1) Quantify snow mass and physical properties across topographic and vegetation gradients in different snow environments (e.g. temperate and Arctic) and across the snow accumulation and ablation seasons. (Pursuant to Q1 & Q2)</td><td>• Capture accumulation and melt events
• Measure states and fluxes of mass and energy components:
Precipitation
Wind Redistribution</td><td><u>TRL6 or higher required for answering all Mission Objective questions (except 3A, 3B, 3C)</u>
<u>Lidar</u>
• Full-waveform LiDAR system with <1.0 m horizontal resolution and <0.10 m vertical accuracy</td><td>• Field locations representing combinations of topographic, vegetation, and latitude gradients
Range of forest from open to closed
Range of vegetation types</td><td><u>Ground Obs. Data</u>
• Ground observation logs and data records
• Instrument metadata</td></tr>
</table>

A. What is the spatial variability of snow mass and physical properties across topographic and vegetation gradients in different snow climates? B. What factors control variability in snow mass and physical properties across topographic and vegetation gradients? C. How do the spatial variabilities of snow mass and physical properties evolve through the accumulation and melt seasons? D. What factors control variability in snow mass and physical properties at different times in the accumulation and melt seasons? **2) Quantify snow mass and physical properties in boreal and temperate forests, covering a range of canopy densities and latitudes, to improve understanding of the surface hydrology response to snowmelt (Pursuant to Q2)** A. What is the spatial and temporal variability of snow mass and physical properties across a latitudinal gradient of forested areas including boreal and temperate forests,? B. How does canopy density and other factors control variability in snow mass and physical properties,surface energy balance, and the timing of snowmelt, in boreal and temperate forests? C. What factors (for example subsurface properties such as freeze/thaw soil state) control the relative contribution of snowmelt to each annual water balance component in boreal vs temperate forests? What are the uncertainties in estimates of each component? **3) What is the sensitivity & accuracy of different sensors in measuring snow mass and physical properties (or their components)? (Pursuant to Q1 & Q2)** A. At different times in the accumulation and melt seasons? B. In different vegetation cover conditions? C. In varying topographic complexity? D. In varying atmospheric or cloud cover conditions?	SWE change In/Out Solar In/Out Longwave Turbulent fluxes ● Multi-sensor airborne measurements at a spatial scale <200 m to measure: *Snow water equivalent* - Snow depth - Snow density *Spectral & Broadband Albedo* Hyperspectral VIS/SWIR reflected radiance *Snow areal extent* - VIS/NIR imagery (multi- or hyperspectral) - High-res digital photography ● Assimilation model to simulate spatial and temporal evolution of snowpack in accumulation and melt seasons ● Concurrent *in situ* ground truth measurements of micro- and macro-snow & forest properties - Depth, density, SWE - Grain size & morphology, - Snow surface roughness - Snow stratigraphy - Snow temperature profile - Forest litter content in the snow surface layer - Forest structure metrics including tree height, crown radius, and forest density. - Soil moisture, roughness - Short vegetation - Calibration for certain airborne observation - In situ tower radiation and energy balance. Four component radiation (SW, in and out, LW in and out) - Wind speed and direction - Relative humidity - Air temperature - Snow & soil temperature profiles - Barometric pressure - Spectral albedo - Interception	<u>Vis/IR/SWIR</u> ● VIS/NIR/SWIR imaging radiometer/spectrometer (FOV ≤80° , spectral range 300-2200 nm, iFOV < 1deg.) ● albedo accuracy <5% ● Imaging IR sensor and remote thermometer(accuracy ±1K) ● High res digital RGB imagery from multiple platforms (incl. small drones) <u>L-band and Ka-band InSAR</u> ● L-Band and Ka-band frequency (~ 1 and 25 GHz) ● Dual-polarized or quad polarized ● <10° phase sensitivity ● <5 m horizontal resolution <u>Active microwave</u> ● Dual-pol radar (10 & 17 GHz) with spatial resolution of <10 m and a swath width of >100 m, Backscatter sigma 0 to -20 dB <u>Passive microwave</u> ● Dual-polarized microwave radiometer (minimum bands: 10, 18, & 37 GHz); spatial resolution <200 m, TB accuracy of ±2K <u>Ground Observations</u> ● SWE accuracy: 2cm (SWE <20cm), 10% (SWE >20cm) ● Snow density accuracy: 20 kg/m^3 or 2% ● Snow depth accuracy: 3 cm ● Snow temperature: 1°C. ● Snow grain size: 0.2 mm (<1 mm), 1 mm (1-15 mm) ● Snow liquid water content (quantitative observations required; dielectric in-situ probes, not hand wetness test) ● Field spectroscopy VSWIR of spectral radiance, spectral irradiance, and spectral albedo ● Broadband and spectral in situ albedos	Range of terrain to capture topographic-scale and wind redistribution processes ● Field sites with accessibility for field crews to operate efficiently and safely ● Field sites with historical meteorological data from in-situ weather stations, previous field campaigns, and streamflow monitoring ● Airborne platform(s) with flexible range and altitude capabilities matching optimum sensing altitudes (e.g.,1000-6000 ft AGL), with capacity for multiple instruments and flight profiles ● Fully coordinated airborne and in-situ snow surveys at nested scales during the field season ● Temporal resolution — daily ground observations during airborne observations (at least 2 8hr-flights per week) at least two weeks in winter and one week in spring. Timing to capture precipitation, redistribution, and melt events Continuous in situ observations of snow depth and/or SWE at multiple locations through full snow season ● Physical, empirical, and/or statistical snow distribution models to scale ground measurements to airborne and satellite remote sensing scales ● Spatial scaling models ● Radiative transfer and scattering (Forward) models ● Snowpack physical models including snow redistribution and interception components ● Snow physical models ● SWE retrieval algorithms ● Atmospheric models for assimilating ground station data and providing forcing data for snow models	● Raw observations, and catalogued and corrected observations, measurement, and calibrations ● Filtered forest litter snow samples ● Local meteorological and radiation observations ● Local hydrological data ● QA/QC'd in-situ data produced while still in the field. <u>Airborne Data</u> ● Level 0 raw instrument and engineering data stream for each flight ● Level 1 radiometric and geometric corrected data (i.e., brightness temperature, TB, backscatter, surface directional reflectance), InSAR phase and coherence, Lidar surface elevation models ● Level 2 geophysical parameter data (SWE, albedo, BRDF, BRF, HCRF …) ● Level 3 gridded data integrating airborne and ground measurements for select locations (e.g. SWE values and evolution over the season, albedo vs SWE relationships) ● Level 4 results from models incorporating L3 data ● Ancillary satellite data collected during field campaigns <u>Ground-based RS</u> ● Level 0 raw instrument and engineering data stream ● Level 1 radiometric and geometric corrected data (i.e., brightness temperature, TB, backscatter) ● Level 2 geophysical parameter data <u>Models Data</u>

4) What are the optimal spatial and temporal observation scales to capture variation in snow mass and physical properties? (Pursuant to Q1 & Q2) A. Driving mass and accumulation dynamics? B. Driving energy balance and melt dynamics?	• Ground-based RS to provide time series prior and between airborne RS obs • Measurements of other hydrologic variables (streamflow, evapotranspiration)	• Aerosol total column optical depth, aerosol size distribution, columnar water vapor, etc. • 3-D Terrestrial Laser Scanner (TLS) to characterize stand scale forest structure characteristics within a 300-m diameter area. • Portable VIS-NIR field spectrometer • Hemispherical photos using a digital camera such as Nikon Coolpix 995 with a levelled fish eye lens, at 50-m intervals and analyzed using Gap Light Analyzer 2.0 • Snow samples for filtration to determine forest litter content. • Streamflow accuracy 10% • ET accuracy 20% • Ground-based microwave radar for profiling snow depth/ SWE/snow density/LWC, and for simulating airborne radars • Full energy-balance automatic weather stations • SnowMicroPenetrometer for stratigraphy, microstructure • IceCube SSA observation • cm-level GPS surveying of field observations		• Algorithms for process and ingest of SnowEx data into hydrologic and radiative transfer models • Data documenting Improvement of hydro models using SnowEx results • Model setup/initialization files, forcing data used, model output of snow/soil states..

4.2. Overarching strategy

SnowEx is a multi-sensor, multi-year snow campaign that will investigate the distribution of snow water equivalent and the surface energy balance in different forest types and densities and terrain. The overarching strategy is to conduct airborne snow remote sensing using multiple sensors while implementing coincident in situ field observations and ground-based remote sensing. More specifically, SnowEx will use a unique combination of sensors, including LiDAR, active and passive microwave, an imaging spectrometer and infrared sensors to determine the sensitivity and accuracy of different remote sensing techniques for measurement of SWE and constraining the energy balance at the snow surface. Cross-sensor comparisons and comparisons to the ground-based instruments and snow field measurements will enable quantification of relative sensor uncertainties, influence of physiographic variables (e.g., increasing forest density) on remote sensing accuracy/capability, and detailed analyses of physical processes and scaling through coordinated modeling experiments. A suite of airborne, ground/in-situ, and modeling data are required to address the science questions of SnowEx.

The general strategy of a SnowEx field campaign is to investigate how the spatial gradient of a confounding physiographic factor influences the accuracy of snow remote sensing, while simultaneously addressing one or more gaps in snow science (see section 2). As much as possible, the gradient of interest should be free of additional varying factors in order to provide a more controlled environment to test the influence of that physiographic gradient on snow remote sensing. Another important element of the SnowEx strategy is to assess how snow remote sensing uncertainty evolves through the course of a snow season, as the measurement uncertainty quantified during one part of the snow season (e.g., mid-winter with drier, colder snow) may not be representative in other parts of the snow season (e.g., spring melt season with wetter, warmer snow). This suggests a time-series experiment, which is a major focus of SnowEx 2019.

4.3. Research Phases and Timeline

SnowEx is a ~5 year mission designed to address the science questions and objectives articulated by the community (see STM). The program spans over 2016-2021, a period that overlaps with other relevant NASA missions (e.g., IceBridge, ICESat-2, Airborne Snow Observatory, and ABoVE) that offer opportunities for leveraged activities. SnowEx has three phases: initial field campaign, community synthesis, and outyear field campaigns.

Phase I (2016-2017) includes the initial field campaign that targeted the impact of increasing forest density on both snow remote sensing uncertainty and on snowpack processes. This field campaign was executed in Colorado, with intensive airborne remote sensing and ground-based observations in Grand Mesa, Senator Beck Basin, and the Fraser Experimental Forest.

Phase II (2017-2018) is a one-year synthesis period intended to allow the community to assess observational and modeling results from Phase I, to build consensus on research priorities in Phase III (and beyond), and to create implementation plans for future campaigns.

Phase III (2018-2021) will implement multiple winter field campaigns with paired airborne remotes sensing and ground-based observations to address the science questions and objectives of SnowEx. Based on the recommendations from the gap prioritization (§3), the proposed study domains and regional characteristics include:

- **2018-2019: mountain ranges and time variations of snow in the western United States.** Field campaigns in three Regional Study Areas - Colorado, California, and Idaho will permit testing of SnowEx science questions in several gaps: forest snow, maritime (deep/wet) snow, mountain (steep) snow, prairie snow, and wet snow. Opportunities exist during this time frame and these locations to leverage ASO operations and lidar mapping by FEMA over Idaho.
- **2019-2020: Arctic tundra and boreal forests (taiga) of North America.** SnowEx and ABoVE leadership are in discussions about the potential for coordinated observations.
- **2020-2021: either a focused prairie snow campaign or a maritime gradient campaign that might also include prairies.** The selection of this campaign is contingent on results from the prior SnowEx campaigns. Flexibility is planned to allow for addressing the most major outstanding questions at the end of SnowEx.

4.4. Remote Sensing: Requirements and Risk Management

Global and regional seasonal snow covers are changing rapidly, and our understanding of these changes are best understood through the integration of remote sensing, modeling, and field investigations. Snow-covered extent has dropped markedly in the past 30 years, and this snow cover reduction rivals that of Arctic sea ice. Other studies provide strong indications that the prevalence of rain-on-snow is also increasing, from which we can infer that the partitioning of liquid vs. solid precipitation is changing in favor of less snow. The rapid changes listed above are worrisome because they imply that the most important metric, the amount of snow, is also changing rapidly. We have only the poorest knowledge of this metric, and that knowledge deficit extends across a wide range of scales. Not knowing the current amount of snow on Earth, clearly we also do not know how that amount is changing. At present snow remote sensing efforts deliver, at best, relatively poor quality and low resolution information.

SnowEx aims to identify the most robust snow remote sensing approaches which will enable measuring and quantifying current snow amounts and snowmelt, and future trends of SWE. Therefore, SnowEx will test a suite of remote sensing instruments (see section 2.1.2) which provide information relevant to SWE or the surface energy balance from different measurement principles. SnowEx will require remotely sensed observations of snow water equivalent, snow depth, areal snow cover extent, and radiometric properties (albedo and VIS/SWIR reflectance, surface temperature, brightness temperature) to address the questions in the STM.

By design, SnowEx will provide quantitative insights into the risk management of a suite of remote sensing instruments with respect to specific confounding factors introduced by the landscape (e.g., forest gradients, liquid water content, deep snow). In lay terminology, SnowEx aims to find the “breaking point” of different technologies and the conditions and scales at which the remote sensing technology is most reliable. Beyond these “breaking points” there will exist additional limitations (e.g., cloud cover, wet snow) that are unique to each sensor. These risks will be specifically managed and mitigated on a sensor-by-sensor basis with expert knowledge and logistical flexibility. A specific interest of SnowEx is to examine how multiple remote sensing instruments may be used in concert to overcome limitations and optimize information content of snow states.

4.5. Role of Models Data Assimilation in SnowEx

Models provide a key supporting role for synthesising and interpreting data collected from snow remote sensing instruments in SnowEx. Models and remote sensing will have a synergistic relationship in SnowEx, where snow remote sensing data can provide evidence of model strengths and limitations and in turn models can help identify areas of high uncertainty and additional needs for intensive field and remote sensing observations. Furthermore, models are essential for filling gaps in remote sensing data, which may occur in space (e.g., when a confounding factor like forest cover overwhelms the remote sensing signal) or in time (e.g., between data acquisitions from an airborne or spaceborne platform). Understanding the tradespace of different remote sensing techniques and configurations is not possible without considering modeling capabilities and accuracy in tandem. The integrative application of snow remote sensing data into models via formal data assimilation methodologies has the potential to provide the most comprehensive picture of snow cover characteristics in space and time; indeed, there are conditions and resolutions that no sensor strategy can overcome. Therefore, models and data assimilation will enhance the experiments and data of SnowEx through applications before, during, and after field campaigns. SnowEx field and airborne experiments must consider forcing data available for models, as well as field observations designed to test both remote sensing retrievals directly, as well as integrated quantities such as stream flow that can be used to test results of combined model and remote sensing approaches.

4.6. Anticipated Outcomes

SnowEx offers multiple benefits to the snow science community. SnowEx will enhance collaborations between researchers across international borders and between subfields within snow science (e.g., mountain snow and high latitude snow researchers). The program will also help develop the next generation of snow scientists, which is especially important when considering the water-related challenges of the 21st century. Quantifying snow distributions and energy dynamics is becoming ever important with declining snow cover due to global change and increasing regional water demand. SnowEx will equip the community with tools to better quantify snow amounts and their changes in time.

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Appendices

Appendix A: Gaps Writeups

A.1 Forest Snow

Scientific Importance

“The boreal forest (taiga) is Earth’s largest terrestrial ecosystem, covering about eleven million square kilometers (7% of the global land surface area) with snow cover that lasts six to nine months a year. An estimated four million square kilometers of forest in the mid-latitudes have related snow properties. These forest snow covers play a crucial role in global biogeochemical and ecological cycles. Studies have linked snow accumulation in mid-latitude forests to forest health. Throughout forests, rising temperatures and earlier spring snowmelt have increased the frequency of forest fires." adapted from Got Snow (Sturm et al., 2016).

In addition, surface albedo of boreal forests in the presence of snow contributes to a large intermodel spread in simulated surface albedo in the Coupled Model Intercomparison Project Phase 5 (CMIP5). Some studies (e.g. Qu and Hall, 2013), have shown that this spread is largely responsible for uncertainties in simulated snow-albedo feedback strength which accounts for much of the spread in simulated 21st century warming at northern high latitudes. The quantification of snow albedo and separately vegetation albedo with VSWIR imaging spectroscopy is critical to reduce these modeling uncertainties.

Also, understanding the effect of forest canopy on snow metamorphic rates is necessary to mathematically represent the physics of snow evolution under forest canopies (see Molotch et al. 2016).

Measurement Challenges

"Our ability to measure snow in forests has been limited because existing remote sensing technologies cannot fully see snow through tree canopies." adapted from Got Snow. Forest canopies significantly reduce passive microwave sensitivity to snow depth/ SWE at Ka- and Ku-band. Forests also reduce scatterometry signal sensitivity to SWE; the CoreH2O proposal only claimed to be able to estimate SWE where forest fraction was <20%. Recent work has shown that when you have gaps in forest canopies, it is possible that snow under the forest canopy is observable by Ku. Traditional radiative transfer models do not represent this correctly, but this behavior is underconstrained by observational datasets. Forests pose less of a problem for LiDAR as laser returns come not only from the canopy but also the substrate surface; however, it is expected very dense canopies will affect LiDAR-retrieved snow depth accuracy. At L-Band frequencies, radar applications have leveraged the ability to penetrate some vegetation and forest cover; however, with the presence of snow, it is not well understood whether L-Band interferometric coherence is maintained and whether changes in phase can be modeled to represent changes in SWE underneath forest canopy and within some vegetation.

- We need measurements of canopies and radar.

Campaign Objectives

Pulled directly from SnowEx Experiment Plan v6.

1. Quantify SWE in open and forested areas for different canopy densities and terrain to address the following questions:
    a. What is the spatial variability of SWE in open and forested areas?
    b. What factors control snow variability in open and forested areas in different terrain?
    c. What is the sensitivity & accuracy of different sensors to measure SWE at different scales and under different canopy densities?

2. Quantify snow albedo in open and forested areas for different canopy densities & snow conditions. Specifically, we will address the following questions:
    a. What is the spatial variability of snow albedo in open and forested areas?
    b. How does the average albedo of an area scale as we move from point to plot to hectare to stand and domain?
    c. What is the sensitivity & accuracy of different sensors to snow albedo at different scales?

Expected Outcome

Pulled directly from SnowEx Experiment Plan v6.
The result will be a major leap forward in our ability to estimate global SWE and albedo and toward defining a new snow space mission concept.

Addressing the 'forest gap' will quantify the accuracy of SWE retrieval in a major land cover category, and help set appropriate limits on when/where we can expect to get retrievals at what accuracy. This, in turn, will help define a future snow satellite mission concept.

A.2 Mountain Snow

Scientific Importance

"Mountain snow tends to be deep, up to thirty meters in maritime ranges, and thus often exceeds the saturation limit for microwave-based methods for determining SWE. Steep slopes, widely varying exposure, and substrate ranging from rock to organic soil also confound microwave signals. Airborne lidar and photogrammetric techniques, with their high resolution, show promise but the trade-off is limited spatial coverage, precluding measurement over large areas. In mountain snow, measuring both the SWE and albedo is critical so as to understand how the timing of melt is changing." from *Got Snow*. For regional water resources, mountain snow is a natural reservoir where water during the cold season is retained and later released during the warm season as snowmelt when water demand is higher. Mountainous areas provide more streamflow than corresponding lowland areas downstream [Viviroli et al., 2007], and in many mountain ranges globally the majority of precipitation falls as snow. Beyond water supply, mountain snow has important implications for ecological functioning, hydropower production, and natural hazards (avalanches and transportation corridors in mountains). The quantity of mountain snowpack is changing, as long-term observations show declining mountain snowpack in over 90% of locations in the western United States (Mote et al., 2018).

Measurement Challenges

The amount and characteristics of mountain snowpack can vary considerably inter- and intra-annual, between mountain ranges, and across mountain ranges. Snow depth and SWE exhibit complex multi-scale patterns [Deems et al., 2006] with different processes acting at different scales. Snow drifting and vegetation can control local scale (10^0 to 10^3 m) patterns while orographic precipitation, freezing levels, and melt energy dominate watershed scale patterns in mountain snow [Clark et al., 2011]. A mountain watershed can have wetter, denser snow at lower elevations and drier, lower-density snow at upper elevations, resulting in a unique measurement challenge.

Passive microwave remote sensing has had limited success in mountain snow due to the variable depth and liquid water conditions acting across areas with complex terrain and vegetation [Nolin 2010]. Active microwave (e.g., SAR) has shown promise for providing more resolved maps of SWE (~10^0 to 10^2 m resolution). Recent work has used a priori information (e.g. snow hydrologic models) to resolve the dependence of Ku-band radar on SWE for deep snow, up to potentially 300 cm in depth. Timeseries approaches can be used to infer snow accumulation even when most of the microwave signal does not penetrate the entire snowpack, similar to passive microwave [Li et al., 2017]. Mapping SWE using lidar altimetry and a snow density model has shown success [Painter et al., 2016] across large mountain basins, and has fewer limitations in forests than SAR. However, lidar approaches are challenged by clouds. Space-borne photogrammetric approaches (e.g., structure-from-motion) can resolve snow depth at fine scales with less precision than lidar, but are also challenged by clouds. For interferometric methods, a change in SWE that results in a phase change greater than 2π radians results in an ambiguous interferometric product. Deep snow accumulation is thus an issue for L-band, and needs to be further explored.

Campaign Objectives

1. Quantify the distribution of SWE over mountains and assess optimal approaches for mapping SWE.
2. Quantify how the surface energy balance varies in complex terrain and through the snow season.

Expected Outcome

Pulled directly from SnowEx Experiment Plan v6.
The result will be a major leap forward in ability to map snow water equivalent from remote sensing observations.

Addressing the ‘mountain snow gap’ will provide information in a hydrologically significant area that has had no reliable remotely sensed SWE in the past.

A.3 Tundra Snow

Scientific Importance

Tundra is the most representative biome of arctic land regions underlain by permafrost, covering ~8 million square km (~5.4% of the land surface of the earth vs. 7% for boreal forest). The largest observed climate changes (warming) have been observed in arctic areas [ref]. The retreat or advance of permafrost areas serves as a good indicator of long term regional and global warming or cooling trends because permafrost temperatures reflect the integrated effect of years and decades of surface temperature conditions. (*adapted from Kim 1998*).

Warming promotes thawing of permafrost which affects the hydrology of the arctic through a deeper active layer (the upper portion of the tundra and permafrost which thaws during the summer), increased soil moisture storage, warmer soil temperatures, increased evaporation, and release of long-sequestered carbon. The heat & water inputs & losses in and out of the active layer are modulated by the snowpack—which often exists for 9 months per year. i.e., tundra snowpack characteristics (insulating power, albedo, SWE) are key drivers of the surface thermal & hydrologic regimes. Snow depth affects the ability of grazing fauna to feed (therefore affecting migration patterns), and the timing of overland transportation for subsistence and industrial activities. (*adapted from Kim 1998*).

Many tundra areas are technically classified as deserts on the basis of low annual precipitation, and the generally flat terrain might suggest a hydrologically unimportant area. However, decades of research shows that the presence of impermeable permafrost and saturated soils lead to tundra hydrology being very sensitive to small changes--which are then multiplied by large areas. For example, slight variations in microtopography control slight changes in water levels which then control whether the active layer biochemical processes are primarily aerobic or anaerobic—the latter being a source of the potent greenhouse gas methane.

Measurement Challenges

The snow measurement challenge in tundra areas is tied to the relatively thin snowpack (<1m depth, and 0.35m is not unusual), huge metamorphic changes inside the pack over the winter (due to thermal gradients >100K/m), and a rapid melt (e.g, 1 week). In terms of spatial resolution, while there is certainly spatial variability at scales down to decimeters, mean depth and SWE are more spatially uniform than in areas of complex terrain.

Measurement techniques that require solar illumination will not work during the polar winter, and even when the sun is above the horizon, solar angles will be low. Microwave techniques will not experience issues. Lidar and photogrammetric approaches (e.g., structure-from-motion) will have to contend with cloudiness. Polar-orbiting sensors will provide more observations per day near the poles vs. mid-latitudes. Multi-frequency Ku-band approaches are hampered by the difficulty in separating the radar backscatter originating from substrate from the snow volume scattering, as well as the exceptionally large grain size and significant density stratification. At Ku-band, it is likely that the radar signal penetrates the organic soils, thus further complicating the retrieval problem. C-band measurements are being explored to help better resolve this dynamic.

Campaign Objectives

Pulled directly from SnowEx Experiment Plan v6.

1. Quantify SWE in tundra areas to address the following questions:
    a. What is the spatial variability of SWE & depth over tundra areas?
    b. What factors control SWE & depth variability in tundra areas?
    c. What are the sensitivity & accuracy of different sensors to measure SWE at different scales in tundra areas?
2. Quantify snow albedo in tundra areas. Specifically, we will address the following questions:
    a. What is the spatial variability of snow albedo in tundra areas?
    b. How does the average albedo of an area scale as we move from plot scale to passive microwave footprint scale (10km)?
    c. What is the sensitivity & accuracy of different sensors to snow albedo at different scales?

Expected Outcome

Pulled directly from SnowEx Experiment Plan v6.
The result will be a major leap forward in our ability to estimate global SWE and toward defining a new snow space mission concept.

Addressing the ‘tundra gap’ will quantify the accuracy of SWE retrieval in a major land cover category (by areal extent), and help set appropriate limits on when/where we can expect to get retrievals at what accuracy. This, in turn, will help define a future snow satellite mission concept.

A.4 Prairie Snow

Scientific Importance

“Prairie and tundra cover over 32 million square kilometers, or about 21 percent of the land surface area of the planet. The generally thin (20 to 60 cm) snow cover in these areas lasts weeks to as much as nine months of the year. With current technology, we are unable to determine whether the dramatic decrease in June snow extent (see graph page 12) is due to earlier melt because of less SWE, due to higher spring temperatures, or a combination of both.” from *Got Snow.* Prairie and tundra snow are roughly equal in their spatial extent, with prairie snow dominating for latitudes <50°. Note that snow cover in the midlatitude (where prairie snow dominates) is changing faster than for tundra, taiga or alpine snow [Mudryk et al., 2017].

Measurement Challenges

Snowpack is generally shallow, and thus can be analyzed with microwave observations. As snow is mid-latitude, and generally warmer, wet snow is an issue, especially in shoulder seasons. In shallow snow, recent work increasingly highlights the importance of soil type, moisture, and freeze-thaw state. The impact of shrubs and other vegetation is also crucial.

Current radar retrieval algorithms rely on differencing the backscatter measurement from autumn from the mid-winter observation. It is not clear that this strategy will work in prairie snow, as the freeze-thaw state will also be changing in time. Radar algorithms are generally not highly sensitive to snow density. The new retrieval algorithms use a priori data, almost as a classification of snow type. Active areas of research include 1) how to subtract the background from the radar signal, and 2) better “classification” e.g. based on grain size, and other “hidden” or nuisance variables such as the soil permittivity (which may be changing through time). Various approaches use other datasets such as passive microwave, RadarSat (C-band) and TerraSAR-X. Ice lensing and melt-refreeze events will make retrieval complicated in some cases; lower latitudes will be more likely to experience warmer mid-winter temperatures leading to sporadic events. Lidar methods precision of 10 cm is potentially inadequate in areas with very shallow depths.

Campaign Objectives

1. Quantify SWE over a range of soil type, soil moisture, freeze-thaw states, and vegetation types. [Need to articulate sub-questions.]
2. Quantify snow albedo over a range of soil type, soil moisture, freeze-thaw states, and vegetation types. [Need to talk to others about this.]

Expected Outcome

Pulled directly from SnowEx Experiment Plan v6.
The result will be a major leap forward in ability to map snow water equivalent from remote sensing observations.

Addressing the ‘prairie gap’ will quantify the accuracy of SWE retrieval in a major land cover category. This, in turn, will help define a future snow satellite mission concept.

A.5 Maritime Snow

Scientific Importance

Maritime snow covers over 3.6 million square kilometers [Sturm et al. 1995], or about 2% percent of the land surface area of the planet. The generally deep snow cover (1.5 to greater than 30 m) in these areas lasts on the order of weeks in the lower elevations to as much as nine months of the year in the higher elevations. With current spaceborne technologies, we are unable to determine the degree to which the decrease in maximum annual SWE observed over the past several decades is due to increased snowmelt or due to decreases in the fraction of total precipitation that falls as snow.

Measurement Challenges

Snowpack is generally deep, and thus cannot be effectively measured with passive microwave observations. Observations of snow depth using LIDAR are accurate to within 10 cm across mountain landscapes, in open and forested areas, independent of the absolute snow depth. SWE observations using active microwave techniques have had limited success but are theoretically possible. As snow is mid-latitude, and generally warmer, wet snow is often an issue, even in winter, but especially at lower elevations and during the shoulder seasons. In deep snow, recent work on volume scattering techniques increasingly highlights the importance of snowpack stratigraphy, snow grain size and grain shape with regard to backscatter behavior. The impact of shrubs and other vegetation is also crucial.

Current radar retrieval algorithms rely on differencing the backscatter measurement from autumn from the mid-winter observation. It is not clear that this strategy will work in maritime snow, given the prevalence of wet snow and relatively complex snowpack stratigraphy associated, for example, with relatively common development of ice lenses within the snowpack.

Another challenge in more temperate regions is the common occurrence of cloud cover which limits the applicability of LiDAR and optical remote sensing.

Campaign Objectives

1. Quantify SWE over a range of soil type, soil moisture, freeze-thaw states, and vegetation types.
2. Quantify snow albedo and its controls across a range of vegetation and soil types, with additional exploration of sensitivities to soil moisture and freeze-thaw states.

Expected Outcome

Pulled directly from SnowEx Experiment Plan v6.
The result will be a major leap forward in ability to map SWE and albedo from remote sensing observations.

A.6 Snow Surface Energetics

Scientific Importance

Projections of air temperature over the Northern Hemisphere (NH) landmass using the current global circulation models is challenging especially in forested and mountainous regions due to large uncertainties associated with snow albedo feedback.

The snow albedo feedback (SAF) is defined as the reinforcement of melting from (a) decrease of snow covered area from an energy or mass forcing, (b) associated decrease of surface albedo, (c) associated increased absorption of solar radiation and surface heating, (d) atmospheric heating from longwave and turbulent heating, and (e) further reduction of snow covered area from this enhanced energy and/or mass forcing. The SAF is known to enhance sensitivity to climate change in Northern Hemisphere (NH) extratropical global circulation model simulations. However, different global climate models show a large spread in the strength of the SAF, which is mostly attributable to a correspondingly large spread in mean effective snow albedo (e.g. Wang et al., 2016).

Models without explicit treatment of the vegetation canopy in their surface-albedo calculations typically have high effective snow albedos and strong SAF, often stronger than observed, where effective snow albedo corresponds roughly with the type of surface-albedo parameterization used. Models with explicit canopy treatment tend to have lower albedo for surfaces that are completely snow-covered, and a weaker SAF. Hence, in such models either snow albedo or canopy albedo is too low when snow is present, or vegetation shields snow-covered surfaces excessively. So this leads to uncertainties that are largely attributable to uncertainties in the specification of vegetation characteristics in models especially in mountainous areas, where challenges are posed by vegetation, snow spatial heterogeneity, and deep snow. These uncertainties accounts for much of the spread in the simulated 21st century warming at northern high latitudes (Wang et al., 2016; Qu and Hall, 2013).

Measurement Challenges

There is a pressing need to obtain high quality observations of snow surface albedo in forested regions, but landscape heterogeneity complicates our effort to obtain accurate albedo values. Forest clumping, canopy structure and gaps in the forest canopy significantly alters the surface albedo. These geometric optical effects cause surfaces to appear darker when the source of illumination is opposite to the sensor viewing (forward scattering) or brighter when the source of illumination is behind the sensor (back- scattering), significantly impacting the retrieval of accurate snow- covered forest albedo. A higher bidirectional reflectance distribution function (BRDF) could be expected in the viewing direction of forests with wider canopy gaps, where more underlying snowpack would be revealed. It is these shadowing effects that also drive the retention and melt of snow underlying canopy.

There are also challenges associated with representativeness of either ground-based, airborne or satellite albedo measurements (Román et al., 2009; 2011; Wang et al., 2014). So scaling up these datasets to understand entire regions over time has remained a considerable challenge. Both data interpretation and model application become difficult due to these scale issues.

Campaign Objectives

Pulled directly from SnowEx Experiment Plan v6.

1. Quantify SWE in open and forested areas for different canopy densities and terrain to address the following questions:
    a. What is the spatial variability of SWE in open and forested areas?

   b. What factors control snow variability in open and forested areas in different terrain?
   c. What is the sensitivity & accuracy of different sensors to measure SWE at different scales and under different canopy densities?
2. Quantify snow albedo in open and forested areas for different canopy densities & snow conditions. Specifically, we will address the following questions:
   a. What is the spatial variability of snow albedo in open and forested areas?
   b. How does the average albedo of an area scale as we move from point to plot to hectare to stand and domain?
   c. What is the sensitivity & accuracy of different sensors to snow albedo at different scales?

Expected Outcome

Pulled directly from SnowEx Experiment Plan v6.

The result will be a major leap forward in our ability to estimate global albedo and its feedbacks in the climate system, in turn improving our knowledge of climate forcings on SWE and toward defining a new snow space mission concept.

Addressing the ‘forest gap’ will quantify the accuracy of SWE retrieval in a major land cover category, and help set appropriate limits on when/where we can expect to get retrievals at what accuracy. This, in turn, will help define a future snow satellite mission concept.

A. 7 Wet Snow

Scientific Importance

Melting snow provides an essential source of water in many regions of the world and can also contribute to wide-scale flooding, particularly when combined with rainfall. An accurate estimate of the magnitude of snowmelt and the timing of melt runoff is important for water management. The presence of liquid water in the snowpack can be an indicator of snowpack ripening and the onset of spring runoff. Additionally, an accurate estimate of the spatial distribution of snow melt is essential for correctly predicting the runoff response (Lundquist and Dettinger 2005), and will also provide insight into important ecological and biogeochemical processes (Bales et al. 2006). Also, in many areas the largest energy source for melting snow is due to the absorption of shortwave radiation (under most atmospheric conditions),which is dependent on both the incident radiation and the surface albedo and highly variable in space and time. Despite the strong influence of snow albedo on climate, surface energy balance, and melt rates, there is little consensus on which albedo parameterizations are most appropriate for large□scale modeling.

Therefore, the use of satellite remote sensing in the identification of wet snow is of great importance to monitoring of snow-melt process, local climate studies, snow disaster assessment, and water resources management.

Measurement Challenges

Wet snow is radiometrically “opaque” in the microwave frequencies, making measurements of SWE difficult when liquid water exists in the snowpack due to rain-on-snow or snowmelt (e.g. due to shortware radiation absorption). Spring is an important time for monitoring snowmelt runoff, but remote sensing instruments able to offer SWE values (i.e., microwave platforms) cannot “see” through wet snow. So when remote sensing tools are most needed, many space-based sensing technologies for observing snow mass no longer work (adapted from Got Snow).

While SWE estimation is limited by the presence of liquid water in the snow, the sensitivity of many signals shows promise in detecting the timing and spatial distribution of melt. The VSWIR imaging spectrometer can straightforwardly quantify surface liquid water content in snow (Green et al 2006). Microwave measurements are highly sensitive to the snowpack electromagnetic properties as the snow transitions from dry to wet (Mätzler et al. 1980). Ground-based FMCW radar does show some skill in estimating SWE in wet snow (Marshall and Koh 2007), though additional research is needed to assess the signal during the transition period. Altimetric techniques (e.g., Lidar, Ka-band InSAR) are insensitive to the presence of liquid water in snow. Hence, snow depth mapping with these methods is not negatively affected by wet snow. Both of these techniques have return intensities that are sensitive to liquid water content in the snow surface but these have not been quantified or codified yet for algorithm implementations. It is possible that some versions of the multi-frequency SAR hardware could be run in a sort of “interferometric mode”. This should be further validated from airborne platforms.

Campaign Objectives

1. Quantify SWE and wet snow extent over the course of an ablation season. Specifically, we will address the following questions:
    a. What is the spatial variability of wet snow over a watershed during the melt period?
    b. What is the sensitivity & accuracy of different sensors to wet snow at different scales?

Expected Outcome

Pulled directly from SnowEx Experiment Plan v6.
The result will be a major leap forward in our ability to estimate global SWE and toward defining a new snow space mission concept.

Addressing the ‘wet snow gap’ will quantify the accuracy of SWE retrieval during the snow melt season, help identify sensing technologies that can estimate SWE during this critical period, and help set appropriate limits on when/where we can expect to get retrievals at what accuracy. This, in turn, will help define a future snow satellite mission concept.

Appendix B: SnowEx 2017

NASA’s Terrestrial Hydrology Program responded to this urgent need for new observations with the SnowEx mission. The primary goal of NASA’s five-year SnowEx effort is to provide algorithm development and risk reduction opportunities for multiple snow remote sensing and modeling approaches, and generally to lay the groundwork for a future snow satellite mission. An expected feature of a future snow mission is the leveraging of sensors on other satellites, both to enhance coverage and accuracy as well as to minimize cost. Since the mix of available sensors-of-opportunity is dynamic, the need for a multi-sensor baseline field dataset, with high-quality ground truth and available forcing data for models, is essential for quantifying the performance of global snow retrieval in various scenarios of sensor combinations with models.

The Overarching SnowEx/Snow Science Questions for SnowEx 2017 were: How much water is stored in Earth's terrestrial snow-covered regions? And how & why is it changing?

The SnowEx Year 1 Fundamental Questions were: Q1 – What is the distribution of snow-water equivalent (SWE), and the snow energy balance, in different canopy types and densities, and terrain? Q2 – What is the sensitivity and accuracy of different SWE sensing techniques for different canopy types, canopy density, and terrain?

Forested areas have always represented a challenge for snow remote sensing. At peak coverage, as much as half of snow-covered terrestrial areas involve forested areas, so quantifying the challenge represented by forests is an important part of characterizing the expected performance of any future satellite snow mission.

Thus, SnowEx Year 1 campaign (2016-17, but hereinafter referred to as "SnowEx-2017") focused on the distribution of snow-water equivalent (SWE) and the snow energy balance in a forested environment. Specifically, a variety of sensing techniques (passive and active microwave, and passive and active optical, thermal IR) were challenged by a range of forest densities and SWE values in order to understand the strengths and limitations of the techniques for potential use in a snow mission. The SnowEx-2017 sites were Grand Mesa and the Senator Beck Basin, both in Colorado, USA. Nine sensors flew on five aircraft. Dozens more sensors were deployed on trucks, towers, snowmobiles, skis, and on foot as part of a complementary ground-based remote sensing (GBRS) strategy. Nearly 100 participants from North America and Europe collected ground truth during February, 2017.

A broad suite of sensors, including active and passive microwave, and active and passive optical/infrared instruments, were deployed on aircraft. A list of core airborne sensors is as follows. All were from NASA unless otherwise noted.

- Radar (volume scattering): European Space Agency's SnowSAR, operated by MetaSensing
- Lidar & hyperspectral imager: Airborne Snow Observatory (ASO)
- Bi-directional Reflectance Function (BRDF): the Cloud Absorption Radiometer (CAR)
- Thermal Infrared imager (QWIP)
- Thermal infrared radiometer (KT15) from U. Washington
- Video camera

The ASO suite flew on a King Air, and the other sensors flew on a Navy P-3. In addition, two NASA radars flew on G-III aircraft to test more experimental retrieval techniques with proven

InSAR sensor packages at two frequencies, and a combined active/passive microwave instrument flew on a twin otter:

- InSAR (altimetry): Glacier and Ice Surface Topography Interferometer (GLISTIN-A)
- InSAR (phase delay): Uninhabited Aerial Vehicle Synthetic Aperture (UAVSAR)
- Radar and Passive microwave: Wideband Instrument for Snow Measurements (WISM)

The primary Grand Mesa site included a natural gradient of SWE increasing from west to east as well as natural variation in forest cover. The mostly-flat terrain allowed SnowEx-2017 to focus on one confounding factor (forest) without the added complication of another (complex terrain). To address certain hydrologic questions, requiring a gauged basin, the secondary site at Senator Beck Basin, Colorado was added. Although complex terrain was not required to achieve SnowEx-2017's forest objectives, it was a focus of study at the secondary site, since there is little variability in slope and aspect at the primary site.

Five meteorological stations operated in Grand Mesa and two in Senator Beck, providing supporting information on conditions and forcing data for modeling

The main winter campaign took place February 5—26, 2017. Snow-free background observations for the lidar and InSAR altimetry techniques were acquired in late September 2016 using ASO and GLISTIN-A, respectively.

Extensive detailed in situ ground truth measurements were collected, including both traditional techniques as well as newer "high-tech" techniques. A partial list of measurements include snow depth, density, temperature, and grain size/type profiles, snow casts, stratigraphy, spectral radiance profiles, active and passive microwave signatures, precipitation (including high-speed movies), specific surface area, micropentrometer measurements, terrestrial lidar scans, solar photometry, tree motion, and time-lapse cameras.

Data collected from SnowEx-2017 are currently under analysis by a variety of investigators. The forthcoming results of these studies will inform planning for future SnowEx field campaigns and provide quantitative information on uncertainties in remotely sensing snow characteristics in forested environments.

Appendix C: iSWGR Quad Charts

Quad charts on different snow sensors or estimation techniques were presented at the August 2017 iSWGR/SnowEx meeting in Longmont, Colorado. These charts were leveraged to describe the measurement concept and characterize the current capabilities and limitations of each approach (see §3). The quad charts are reproduced below in the same order as they were presented in Tables 1-3.

Differential LiDAR Altimetry

Geodetic calculation of snow depth at high resolution in complex terrain and under forest canopies; SWE retrieval in combination with snow density modeling

Technology Concept:

Measures the difference between snow-covered and snow-free surface elevations using time-of-flight range measurements from an airborne or spaceborne scanning laser system

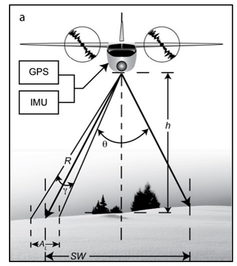
Approach:

Snow depth is calculated by differencing snow-covered and snow-free surface elevations. Partial reflection of laser pulses allows multiple target returns per pulse and mapping below forest canopies.

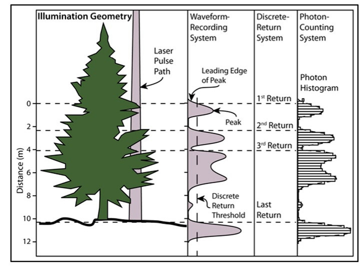
SWE is calculated by integration of measured and modeled snow density; density is far less spatially variable than depth

Ancillary Data Required:

- GNSS/INS, plus GNSS ground control
- Modeled snow density for SWE calculation



Scanning lidar system (airborne example) maps surface elevations



Beam divergence allows multiple returns per pulse using discrete, full-waveform, or photon-counting detection systems

Strengths:

- Direct measurement of elevations
- High horizontal spatial resolution
- High vertical precision
- Can map snow under forest canopy
- Not dependent on solar geometry

Challenges and Development Opportunities:

- Clouds reflect lidar pulse, add noise
- Dense forest canopy reduces surface point density
- Weekly repeat at cost of non-global coverage
- Space-borne LiDAR has larger footprint
- Flash lidar systems: allow pushbroom swath mapping with large footprint laser
- Hyperspectral lidar: broad spectrum light source + hyperspectral receiver allows retrieval of surface properties

Partner User Communities:

- Vegetation structure & biomass
- Cryospheric change
- Landslide detection and floodplain mapping
- Tectonic deformation
- Surface water elevation

Heritage and Technology Status:

- ICESat 1 & 2 Cryosphere Missions
- LIST Topography mapping Tier2 Decadal Survey Concept
- JPL Airborne Snow Observatory, NASA Applied Sciences
- GEDI Lidar, EVI2 selected for ISS deployment

TRL=9 for airborne laser scanning systems
TRL=7 for spaceborne laser scanning systems

SWGR

Dual-Frequency Ku-Band Radar Backscatter

Measures volume scattering response of snow to retrieve snow water equivalent

Technology Concept:

Exploits volume scattering response of snow covered terrain at Ku-band (12 to 18 GHz) to retrieve volumetric properties including snow water equivalent (SWE)

Dual frequency measurements allow sensitivity to higher SWE (~13 GHz) and mitigation of grain size effects (~17 GHz)

Approach:

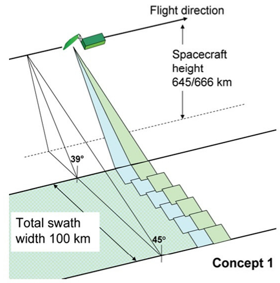
Radar backscatter from snow covered terrain increases with SWE due to the larger path length through the snow volume

SWE retrieved through inversion of physically based radiative transfer models that account for the influence of microstructure

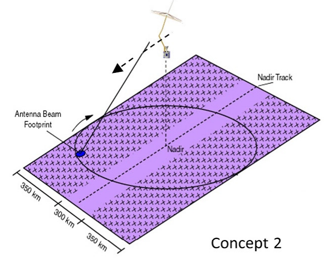
Attenuation and scattering albedo scale differently at the two Ku-band frequencies, so SWE and grain size can be solved together

Ancillary Data Required:

- Snow grain (microstructure) information
- Soil and vegetation parameters



Sidelooking ScanSAR:
Single look high res (~50m)
100 km swath = coverage in 15 days



Rotating SAR:
Single look res (~250m-500m)
700 km swath = coverage in 2 days

Strengths:

- No solar illumination required; penetrates through clouds
- High spatial resolution SWE retrievals (~200 to 500 m after multi-look averaging compared to 25 km for current passive microwave products)

Challenges and Development Opportunities:

- Relating backscatter to physical snow properties complicated by vertical heterogeneity of the snowpack
- The soil contribution must be considered
- Uncertainty in the sensitivity of backscatter to a maximum SWE, and the snowpack controls which determine this threshold
- Snow extent but no SWE retrievals when snow is wet
- Layover and shadowing in complex terrain
- Dense vegetation obscures the snow

Other User Communities:

- Ice sheets and glaciers (snow accumulation)
- Sea ice
- Ocean winds
- Vegetation

International Partners:

- ESA, CSA, FMI, SLF, Meteo-France

Maturity:

TRL=9 for airborne radar systems
TRL=9 for scatterometer; 8 for SAR
Heritage: QuikScat; CoReH2O SMAP (rotating SAR)

Optical Stereo DEMs

Snow depth retrieval using repeat high-res DEMs derived from stereo imagery; SWE retrieval in combination with snow density observations/modeling

Technology Concept:

Along-track (single-orbit) stereo satellite imagery with ~0.3-0.5 m resolution and ~13-17 km swath

DEMs from automated, scalable NASA Ames Stereo Pipeline (ASP)

Approach:

Observations prior to snowfall, repeated during winter/spring

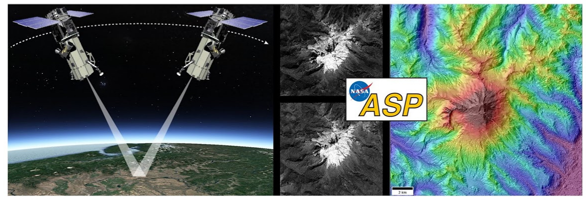
DEM co-registration and differencing to generate time series of snow depth maps

Observed/model density to convert to SWE

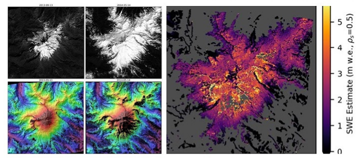
Ancillary Data Required:

Observed/model density (SNOTEL)

Reference elevation control data (ICESat-1/2, LiDAR) [optional]



Along-track stereo image collection. Images and DEM for Mt. Baker, WA



Snow-off (left), snow-on (center) reflectance/DEMs. Peak SWE estimate for WY2014 (right)

Strengths:

- 5 operational DigitalGlobe satellites in sun-synchronous orbits
- On-demand, global coverage, repeat interval <1-2 days
- No direct cost for federal research applications, including stereo archive access (2007-present) and future tasking
- Each DEM: ~1-2 m resolution, up to ~300-7000 km^2
- Relative DEM accuracy <0.1-0.3 m for low slopes
- 4, 8, or 12-band MS images (~1.2-1.9 m res.) for reflectance, vegetation classification

Challenges and Development Opportunities:

- Commercial competition for resources
- Requires solar illumination, dense clouds obscure surface
- DSM only (no returns below dense canopy)
- Data gaps due to occlusions
- Spacecraft "jitter" and sensor geometry artifacts can introduce ~0.1-0.3 m systematic elevation artifacts

Other User Communities:

- Cryosphere (ice sheet and glacier mass balance, dynamics)
- Natural Hazards (landslides, floods, avalanches)
- Solid earth, geodesy, volcanology, geomorphology
- Forestry

Commercial/International Partners:

- DigitalGlobe (WorldView-1/2/3/4, GeoEye-1)
- Planet (SkySat-1/2, Dove)
- CNES/AIRBUS (Pleiades-1A/B, Spot-6/7)
- ISRO (Cartosat-1)

Maturity:

TRL=9

Heritage: DigitalGlobe WorldView-3

1851 **August/2017**

Differential Structure-from-Motion DSMs

Snow depth retrieval using repeat high-res DSMs derived from overlapping imagery; SWE retrieval in combination with snow density observations/modeling

Technology Concept:

Measures the difference between snow-covered and snow-free surface elevations using DSM's reconstructed from overlapping, offset imagery taken from airborne or spaceborne platforms using structure-from-motion

Approach:

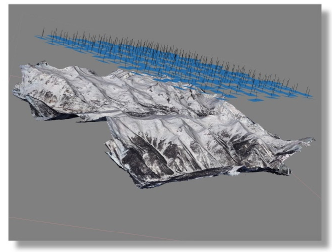
Observations prior to snowfall, repeated during winter/spring

DSM co-registration and differencing to generate time series of snow depth maps

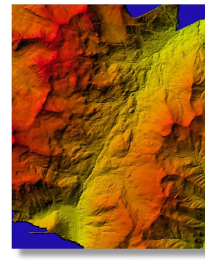
Observed/model density to convert to SWE

Ancillary Data Required:

- GNSS/INS, plus GNSS ground control
- Modeled snow density for SWE calculation



Dense point cloud showing camera positions (ASO RGB camera) over the Senator Beck Basin domain from SnowEx '17 (Feb 21 acquisition- ~350 photos)



Corresponding high resolution DSM of Senator Beck Basin domain from Feb 21, 2017

Strengths:

- High spatial resolution, even in complex terrain
- High positional accuracy (w/ ground control points and/or gnss)
- Colorized/RGB intensity point cloud and DSM
- Inexpensive relative to lidar differential mapping
- Builds on long legacy of photogrammetry and imagery from airborne and spaceborne platforms

Challenges and Development Opportunities:

- Dense clouds and vegetation obscure surface
- Solar illumination required
- DSM only (no returns below dense canopy)
- Frequently applied using short range UAV's, scalable to watershed and regional level with advancing UAV technology/policies
- Potential to combine with imaging spectrometer

Other User Communities:

- Cryosphere (ice sheet and glacier mass balance, dynamics)
- Natural Hazards (landslides, fault mapping, floods, avalanches)
- Solid earth, geodesy, volcanology, geomorphology
- Vegetation
- Urban planning

Maturity:

TRL= 9 for photogrammetry, 6 for SfM application to snow depth

Heritage: Optical stereo DEMs- DigitalGlobe WorldView-3, ASO, numerous UAV applications

1852

Wideband Autocorrelation Radiometry

Passively measure microwave propagation time thru a snow pack

CLIMATE AND SPACE SCIENCES AND ENGINEERING
UNIVERSITY OF MICHIGAN

Technology Concept

Measures round trip propagation delay thru the pack caused by coherent effects of multipath emission

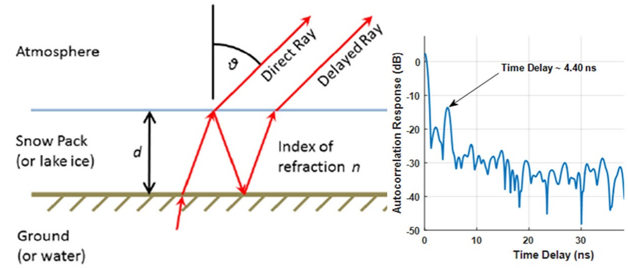
Approach

Long wavelength radiometer with wide bandwidth

Autocorrelation function measured directly or from inverse Fourier transform of brightness spectrum

Ancillary Data Required

Snow depth and SWE are combined in retrieved delay; either will provide the other, or snow density will resolve both



The physical process observed, and a measurement of ice thickness

Strengths:

- Passive microwave: day/night, all-weather, low power
- Scattering (eg. vegetation) and RFI degrade signal-to-noise but do not alter the delay
- Easily integrates with GNSS-R

Challenges and Development Opportunities:

- Shallow snow requires large bandwidth
- RFI in optimal bands for observation
- Large footprints, but
  - Sub-pixel variability?
  - Significant oversampling
- Stratigraphy effects yet to be explored
- Dry snow only

Other User Communities:

- Lake ice thickness
- Snow on sea ice?
- Temperature profiles of ice sheets

Heritage and Technology Status:

- Ultra-WideBand Radiometer (Ohio State U)
- PALS back-end development (JPL)
- Wideband Autocorrelation Radiometer (U Mich)

TRL=6 for airborne hardware (UWBRAD)

TRL=2 for application to snow packs

Snow Water Equivalent Retrievals From Multi-Frequency Passive Microwave

Technology Concept:

Exploits natural emission of underlying soil and frequency-dependent volume scattering response of snow covered terrain at 10—37 GHz to retrieve snow water equivalent (SWE)

Conducted from spaceborne, airborne, or ground platforms

Approach:

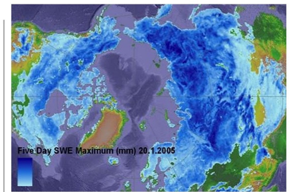
Thermal emission from soil underneath snow is attenuated more as overlying snow increases. Attenuation is greater for larger snow grains and for higher frequencies

SWE is related to difference in attenuation at different frequencies.

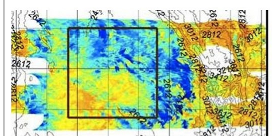
Correction for forest masking can be applied

Ancillary Data Required:

- Snow grain (microstructure/stratigraphy) related coefficient
- Forest cover/density for forest correction
- Lake fraction should be considered/corrected for

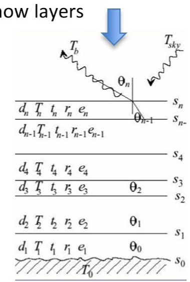


Satellite SWE from AMSR-E



Airborne SWE from 2003 CLPX-1 campaign

Passive emission by soil attenuated by snow layers



Strengths:

- No solar illumination required; penetrates through clouds
- Daily global coverage from satellites
- Detects melt timing
- Very long satellite heritage since NEMS (1972)

Challenges and Development Opportunities:

- Coefficient based on snow grain properties required, even when multiple frequencies used; complicated by vertical heterogeneity of the snowpack
- Sensitivity to SWE saturates at ~150 mm for 19, 37 GHz combo; can be mitigated by adding 10 GHz,
- Thin snow <5cm hard to detect; 89 GHz improves this
- Snow extent but no SWE retrievals when snow is wet
- Dense vegetation obscures the snow; forest correction available
- Moderate/coarse spatial resolution, limits retrieval in complex topography regions
- Availability of future passive microwave satellite sensors uncertain

Other User Communities:

- Ice sheets and glaciers (snow accumulation)
- Sea ice
- SST, SSS, ocean winds, precip (including solid precip)
- Soil moisture, vegetation
- Clouds, atmospheric profiles of temp & humidity

International Partners:

- Japan, Canada, Europe

Maturity:

TRL=9 for airborne & satellite systems

Heritage: SMMR,SSMI, SSMIS, AMSR-E/2,WindSat, sounders

1854

L-band interferometric SAR

Differential repeat-pass interferometric phase measurements provide estimates of snow water equivalent (SWE) for dry snow conditions

Technology Concept:

Changes in snow depth and density affect radar wave speed and refraction causing change in radar wave phase

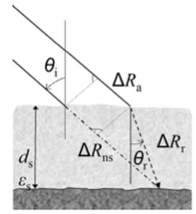
Conducted from ground-based, airborne, or spaceborne platforms

Approach:

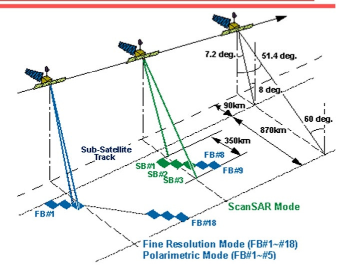
SWE change is estimated by the radar phase difference between two platform passes (using same radar geometry). The phase changes gives a fairly direct measurement of SWE change, capitalizing on the ~linear density-dielectric relationship.

Ancillary Data Required:

- Accurate platform position (via GPS, star tracker, etc.)
- Digital elevation model (DEM)
- Independent SWE estimate at one location (phase ambiguity)



Difference in radar propagation without snow (ΔR_{ns}) and with snow (ΔR_a+ΔR_r) based on refraction. (e.g. Deeb et al., 2011)



Operation modes for JAXA Phased Array type L-band Synthetic Aperture Radar (PALSAR) on ALOS & ALOS-2 platforms (http://www.eorc.jaxa.jp/ALOS/).

Strengths:

- Measurement of SWE change; density not needed a priori
- Radar ability to penetrate clouds and snow
- Does not require solar illumination
- High horizontal spatial resolution (meters)
- Ability to penetrate forest canopy (especially at L-Band)

Challenges and Development Opportunities:

- Phase unwrapping algorithms may fail for complex or abrupt spatiotemporal SWE accumulation patterns
- Need for known SWE change at one location in the scene
- Changes in phase during wet snow conditions
- Consideration of snowpack stratigraphy yet to be done
- Uncertainty of DEM accuracy needed for removal of topographic phase
- Resolving phase change in low-coherence areas

Other User Communities:

- Glacier velocities and mass balance
- Tectonic deformation
- Landslide detection and floodplain mapping
- Permafrost and other cryospheric change
- Changes in surface water elevation

International Partners:

- JAXA, ESA, CSA

Maturity:

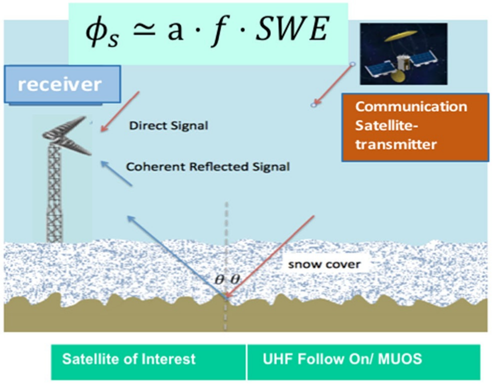
TRL=9 (hardware implementation) and TRL=7 (algorithms and validation) for both airborne and spaceborne

Heritage: ERS and Radarsat SAR (C-band); ALOS PALSAR (L-band)

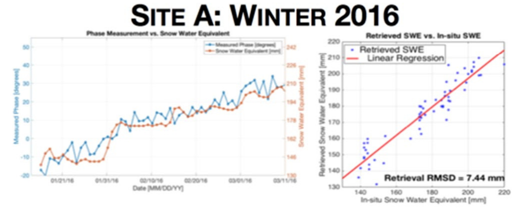
1855

October/2014

REMOTE SENSING OF TERRESTRIAL SNOW USING P-BAND SIGNALS OF OPPORTUNITY



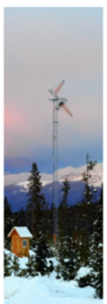
SWE and Phase Change Site A: Winter 2016



- Excellent correlation between SWE and phase change (0.94)
- RMSD with linear regression is 7.5 mm
- Relationship between phase and SWE from experiment matched theory

Shah, R., Xu, X., Yueh, S., Chae, C. S., Elder, K., Starr, B., & Kim, Y. (2017). Remote Sensing of Snow Water Equivalent Using P-Band Coherent Reflection. IEEE Geoscience and Remote Sensing Letters, 14(3), 309-313. doi: 10.1109/LGRS.2016.2636664

SoOp Experimental SetUp



Site A:
- **Almost no vegetation**
- Installed in Fall 2015
- In Winter 2015-2016: recorded data from 240-270 MHz
- In Winter 2016-2017: recorded data from 254-270 MHz and 360-376 MHz

Site B:
- **Vegetation with trees up to 3 meters**
- Installed in October 2016
- In Winter 2016-2017: recorded data from 254-270 MHz and 360-376 MHz

Key points

- P-band SoOp technique effective for SWE (dry snow) or snow depth (wet snow) remote sensing
  - Essentially unaffected by snow density, grain size, and stratigraphy
- P-band can penetration vegetation to sense snow under canopy
- Developing drone for airborne survey

1856 Lead: Simon Yueh, Steve Margulis. To be updated to standard format by Aug 18.

Frequency Modulated Continuous Wave Radar

Measurement of travel-time in snow gives estimates of SWE, snow depth, and stratigraphy

Technology Concept:

A frequency modulated radar pulse is transmitted; the frequency of the returned signal signal is a linear function of two-way travel-time

Broadband (GHz) design – high resolution (1-10cm) allows travel-time between returns (air-snow /snow-ground) to be measured.

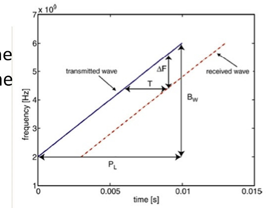
0.5-40 GHz frequencies, GHz+ bandwidths (e.g. 2-10, 8-18, 26-40 GHz). Flexible–can adapt to different conditions/local regulations.

Travel-time is a function of density and wetness, but not grain size

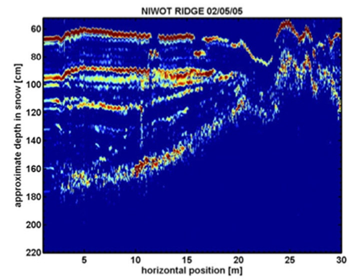
Approach:

Penetrates dry (10+m) and moderately deep wet (1-3m) snow, but not soil/rock. First (air-snow), and last (snow-ground) reflections are auto-detected, and two-way travel-time difference is calculated

Two-way travel time is controlled by depth and average dielectric constant. The dielectric is a function of density and liquid water



Two-way travel time T is calculated from frequency difference ΔF, bandwidth B_w and pulse length P_L [e.g. Marshall and Koh, 2008]



Snow depth and stratigraphy are inferred from the measured two-way travel times between reflections (red=strong, blue=noise floor)

Strengths

Snow Water Equivalent (dry snow) is only ~½ as sensitive to density uncertainty compared to SWE from direct depth measurements

Major stratigraphy (ice layers, large density contrasts) causes reflections, allows extrapolation of layers from in-situ pits

Calibrated system can simulate microwave InSAR and radar scatterometers (L/S/C/X/Ku/Ka-bands)

Challenges and Development Opportunities:

GHz bandwidth not possible from space, but repeat spaceborne InSAR allows same travel-time approach

Possible FCC restrictions in populated areas for airborne deployment

Wet snow: penetration only at lower frequencies, causes under-determined inversion, but possible with new amplitude-based frequency approach (tested only from ground), or local calibration

Penetration through vegetation has not yet been investigated

Other Communities:

- Snowfall - GPM (X/Ku-band). GPM launch in 2016 but snowfall challenging. FMCW likely could help non-unique retrievals
- Soil Moisture/SMAP (L/S/C-band): Reflection from ground is sensitive to soil properties
- Vegetation: lower microwave range can penetrate some vegetation, but limited studies to-date
- High resolution simulation of InSAR/radar scatterometer
- Could provide more IceBridge FMCW coverage & backup
- NASA WideBand Instrument for Snow (WISM) will deploy FMCW + scatterometer/radiometer, Feb 2015, Colorado.

Maturity:

TRL: 7 for ground-based, 7 for airborne over ice sheets, 4 for airborne in the mountains

NASA IceBridge successfully using FMCW radars (Twin Otter/P3) for snow depth and snow/firn/ice mapping

Heritage: ground FMCW systems used for snow science since 70s

October/2014

Gamma

Differential gamma attenuation to map snow water equivalent over unvegetated surfaces

Technology Concept:

Naturally emitted gamma radiation from soils is attenuated by any form of water. Differential gamma radiation measurements can provide accurate estimates of snow water equivalent

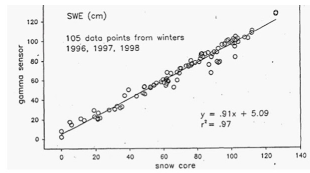
Approach:

Aircraft overflights of transects are flown prior to snowfall and repeated during winter. Regression equations relate gamma attenuation to SWE

Ancillary Data Required:

Empirical calibration of gamma attenuation

NOHRSC airborne gamma survey team



Measured SWE vs gamma-estimated SWE from ground-based sensor

Strengths:

- Direct and highly accurate SWE estimates when soils are dry and water vapor contributions are low
- Works with wet snow

Challenges and Development Opportunities:

- Ground-based and airborne only
- Single value of SWE for each flightline
- Requires low altitude flight lines (500')
- Soil moisture reduces accuracy
- Vegetation reduces accuracy
- Water vapor reduces accuracy
- Challenging to fly over complex topography
- Recent improvement in miniaturization for materials used for gamma detection

Other User Communities:

- Flood forecasting

International Partners:

- None at this time

Maturity:

TRL=9
Heritage: NOHRSC gamma snow surveys

Hyperspectral Imaging Spectrometry

Hyperspectral measurement of reflected light to retrieve snow covered area, snow albedo, surface grain size, absorption by dust/soot/biological particulates, and surface liquid water content

Technology Concept:

Measures reflected solar energy at high spectral resolution in the visible/near-infrared wavelengths

Conducted from airborne or spaceborne platforms

Approach:

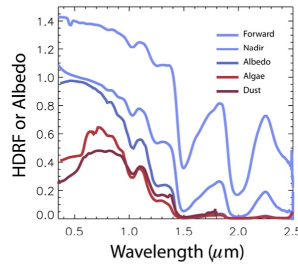
Using radiative transfer models to relate changes in the spectral absorptance/reflectance to quantitatively relate the optical properties of snow to its physical properties.

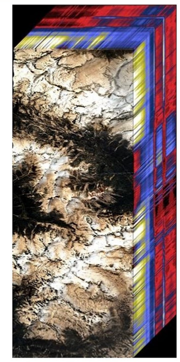
Ancillary Data Required:

Radiative transfer model for albedo, grain size, radiative forcing, melt status

Depth & grain size for thin snow case

Terrain and atmospheric correction





(L) Spectral albedo or HDRF for clean snow, dusty snow, algae-laden snow, and directions. (R) Imaging spectrometer data cube

Strengths:

- Long legacy, mature algorithms
- Physically-based approaches for snow retrievals, including SWE reconstruction
- High SNR
- Highly accurate retrievals of fractional SCA, albedo, grain size, radiative forcing by dust/black carbon; reasonable accuracy for liquid water
- High accuracy of spectral unmixing
- Spatial resolution can be as high as needed

Challenges and Development Opportunities:

- Requires solar illumination
- Clouds and dense forest canopy obscures surface
- Shadowed snow in complex topography and low light can be difficult to accurately analyze
- Surface grain size retrieval only
- Polarization, or multiple view angles could compliment retrievals
- Spatial resolution should be driven by retrievals over mixed pixels/canopy

Other User Communities:

- Vegetation
- Geology and soils
- Coastal ocean
- Inland water quality

International Partners:

- Europe, Australia, Switzerland, India

Maturity:

TRL=9

Heritage: Hyperion, AVIRIS, ASO, CRISM, NIMS, VIMS

1860 **October/2014 (updated SnowEx workshop, Aug 2017)**

Multispectral Imaging Spectrometry

Multispectral measurement of reflected light to retrieve snow covered area, snow albedo, surface grain size, and dust/soot radiative forcing

Technology Concept:

Measures reflected solar energy at moderate spectral resolution in the visible/near-infrared wavelengths

Conducted from airborne or spaceborne platforms

Approach:

Using radiative transfer models to relate changes in the spectral reflectance allows one to quantitatively relate the optical properties of snow to its physical properties.

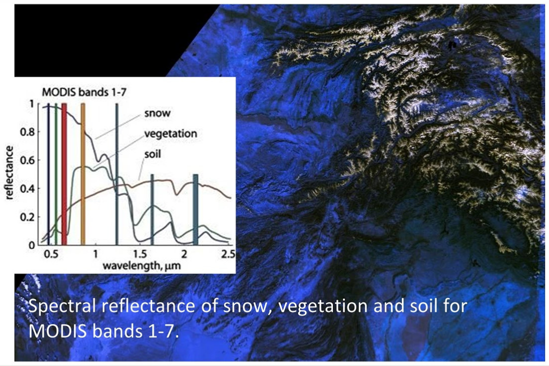
Ancillary Data Required:

Radiative transfer model for albedo, grain size, radiative forcing, melt status

Depth & grain size for thin snow case

Terrain and atmospheric correction

High spectral resolution retrievals of end members for spectral unmixing



Spectral reflectance of snow, vegetation and soil for MODIS bands 1-7.

Strengths:

- Physically-based approaches for snow retrievals, including SWE reconstruction
- High SNR
- Accurate retrievals of fractional SCA
- Modest accuracy for albedo, grain size
- Semi-quantitative retrieval of radiative forcing by light absorbing particulate
- High spatial resolution

Challenges and Development Opportunities:

- Requires solar illumination
- Clouds and dense forest canopy obscures surface
- Discrete bands inhibit quantitative energy flux retrievals, reduce accuracy of spectral unmixing
- Shadowed surfaces in complex topography and low light can be difficult to accurately analyze

Other User Communities:

- Vegetation
- Geology and soils
- Ocean color
- Inland water quality

International Partners:

- ESA, Israel, India, CSIRO

Maturity:

TRL=9

Heritage: AVHRR, SPOT, MODIS, MERIS, VIIRS

Compact, High Resolution Airborne Multiband Infrared Imager

Objectives:

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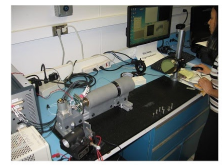
Top: Portable thermal IR camera monitoring lava tubes (caves) in the Mojave desert. This camera also flew on the SnowEx campaign.

Bottom: Recently developed multiband near/thermal IR camera for remote sensing at the International Space Station.



Approach:

- Format 1,024x1,024 broadband infrared detector array into multispectral bands from 1μm to 13 μm.
- Design and build front end customized optics.
- Install multiple filters on the detector array to isolate discreet spectral bands.
- Perform calibration experiments to obtain absolute temperature information.
- Integrate camera control electronics.
- Perform ground-based experiment perform airborne experiments.
- Scale to 2,048x2,048 formats for higher resolution/ wider swath widths.

Key Milestones

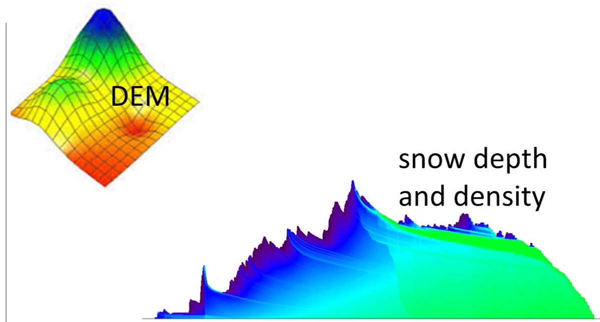
TRL = 5/6

Modeling

Technology Concept:
Using physically-based principles and empirically-fit parameterizations, model how snow accumulates and melts.

Approach:
Use existing observations to develop and calibrate modeling system. Assimilate observations to update model with new observations as available.

Ancillary Data Required:
Snow-off DEM, landcover maps, meteorological forcing



Strengths:
- Everywhere, all the time, at any resolution you want

Challenges and Development Opportunities:
- Quality meteorological data (particularly precipitation) is hard to find in many snow regions
- Models require observations of processes to accurately represent those processes (different processes will be important in different regions)

Other User Communities:
- Hydrology (Water Resources, Flood Forecasting, Reservoir Management)
- Ice (permafrost, glaciers, sea ice)
- Ecology
- Atmospheric Sciences

International Partners:
- None at this time, but lots of potential

Maturity:
TRL=9
Heritage: NLDAS, GLDAS, lots of individual models for local areas